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Test Methods for Composites a Status Report

Volume I. Tension Test Methods

June 1993

Final Report

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16. Abstract

This document provides an evaluation of current test methods for tension properties of composite materials consisting of high modules, high strength fibers in organic matrix materials. Mechanical testing is an important step in the "building block" approach to design of composite aircraft structures. The document provides a source of information by which the current test methods can be evaluated and from which test methods which appear to give good-quality test data can be selected. Problems with current test methods are also addressed as a means of providing recommendations for future research.

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PREFACE

This document is Volume I of three volumes which have been developed to provide an assessment of mechanical property test methods for organic matrix composite materials. The present volume presents a review and evaluation of test methods for tension properties of fiber reinforced composite materials. Two companion documents, Volume II on compression Test Methods and Volume III on Shear Test Methods, have also been prepared.

The present document was developed under an Interagency Agreement between the Federal Aviation Administration Technical Center, Atlantic City International Airport, NJ and the U.S. Army Research Laboratory Materials Directorate, Watertown MA. Technical Direction was provided by D. W. Oplinger of the Federal Aviation Administration Technical Center with the advice of J. Soderquist, FAA Headquarters, Washington DC, while administrative support was provided by R. Pasternak of the Army Research Laboratory Materials Directorate. The work was performed under contract to Materials Sciences Corporation and the Composite Materials Research Group, University of Wyoming. Principal Investigator was Dr. S. Chaterjee of Materials Sciences Corporation with direction of the University of Wyoming effort by Prof. D. Adams.

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EXECUTIVE SUMMARY

This document, which constitutes Volume 1 of a three volume set, provides an evaluation of current test methods for tension properties of "advanced" composites constructed of high modulus, high strength fibers embedded in organic matrix materials such as epoxies. Mechanical testing for various structural properties is one of several essential steps in the design of composite aircraft structures. Companion volumes addressing: Compression Testing (Volume 2) and; Shear Testing (Volume 3) of composite materials, have also been issued. The intention is to provide a comprehensive source of information by which the current test methods for these types of property tests can be evaluated and from which test methods which appear to give good-quality test data can be selected.

The document provides: (1) a comprehensive review of performance features, advantages and negative aspects of various test methods which have been introduced for obtaining tension properties of composite materials; (2) an extensive annotated bibliography covering most documented test method development activity which has taken place since the introduction of advanced composites in the mid 1960's; (3) a ranking of the commonly used test methods for tensile properties, and: (4) an assessment of problem areas that continue to exist in the available test methods.

Results of the survey indicate that straight-sided coupon specimens with bonded loading doublers (tabs) embraced under ASTM test Method D3039 provide test results generally considered acceptable by the testing community. However, there are recognized problem areas associated with stress concentrations introduced by the the tabs which can lead to questionable test results. Testing at high temperature and humidity, which are required testing environments for many composite aircraft components, tends to agravate the problem by promoting tab debonding. Additional studies for the purpose of improved tab designs and gripping arrangements appear worthwhile. The ASTM Standard D3039 is currently being revised with due consideration to the experiences of a wide cross section of the composites community accumulated over a number of years.

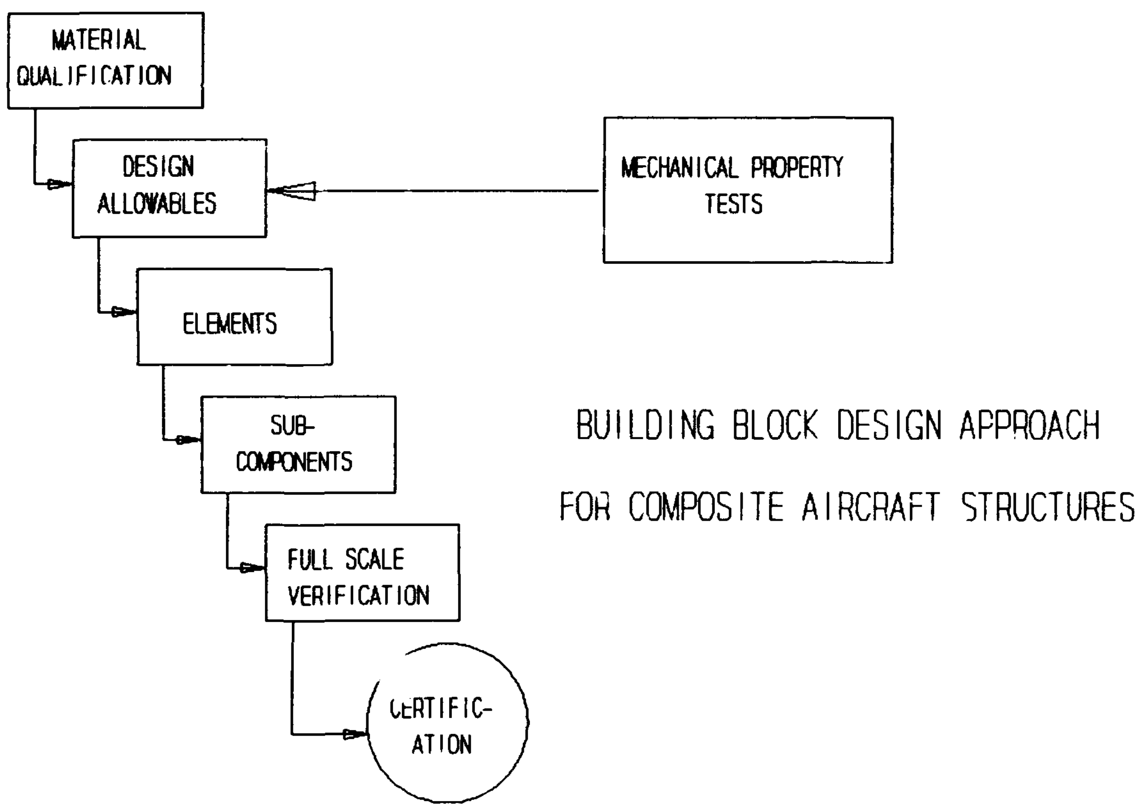
In an attempt to eliminate problems associated with bonded tabs, several untabbed, width tapered specimen designs have been evaluated for tension testing of composites, including ASTM standard D638 (Type 1) dogbone, as well as a linearly tapered design referred to as the "bowtie" specimen, and so-called "streamline" specimens whose shapes are theoretically free from stress concentrations in the tapered part of the specimen. Limited success has been achieved in the testing of unidirectional materials with these approaches. However, these appear acceptible for cross reinforced or fabric materials. Alternative approaches to specimen tapering involving thickness-tapered rather than width- tapered specimens appear promising theoretically, but require investigation.

One additional approach which has been taken for obtaining tensile properties of composites in recent years involves testing of cross-reinforced materials and inferring the properties of unidirectional materials through the use of laminate analysis. Further analytical, experimental and data correlational studies for cross reinforced specimens are needed to evaluate this approach, especially for the development of data reduction procedures which will be acceptable to the composites community.

OVERVIEW

GENERAL REMARKS

This document which constitutes Volume 1 of a three volume set, provides an evaluation of the state of the art of current test methods for obtaining tension properties of "advanced" composites constructed of high modulus, high strength fibers embedded in organic matrix materials such as epoxies. Mechanical testing is an important step in the "building block" approach to design of composite aircraft structures, as illustrated in the Figure below. Companion volumes addressing: Compression Testing (Volume 2) and; Shear Testing (Volume 3) of composite materials, are also available. The intention is to provide a source of information by which the current test methods for these types



Mechanical Property Testing in Composite Aircraft Design

of property tests can be evaluated and from which test methods which appear to give good-quality test data can be selected.

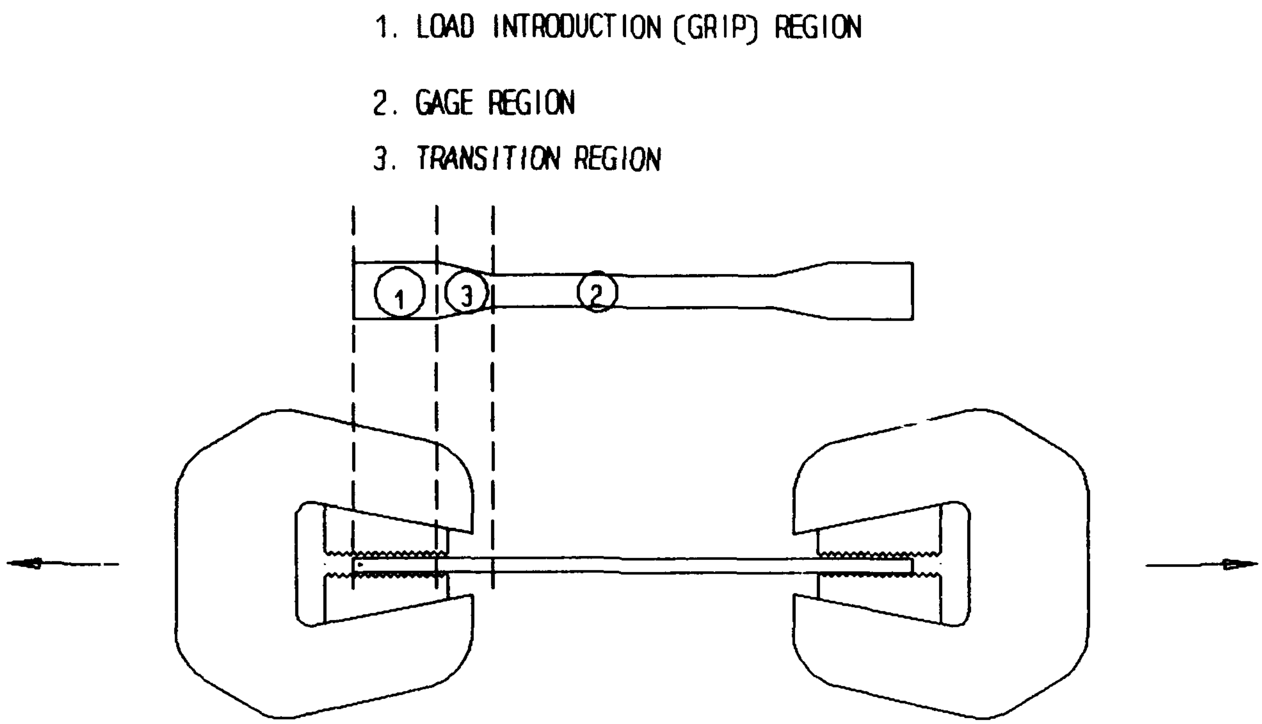
Mechanical property testing of advanced composites has been under development ever since the introduction of such materials nearly a generation ago. The first major conference on test methods for advanced composites, for example, took place in 1969 and culminated in ASTM Special Technical Publication STP 460 which summarized results from a number of DoD programs that were ongoing at that time. The methods which were reported on that occasion formed the basis for a number of test methods which are still in use.

The methodology for obtaining mechanical properties of such materials contains a number of inadequacies and is in need of continuing development. The purpose of this discussion is to review the issues which are significant drivers in efforts toward improved testing methodology, in order to provide a framework for evaluating the state of the art.

OBSERVATIONS ON MECHANICAL PROPERTY TESTING OF COMPOSITES

Mechanical property measurements in structural materials can be characterized in terms of three regions in the test specimen (illustrated in the following Figure for a generic tension test): (1) a load introduction or gripping region, where large stress peaks associated with the load introduction method are compensated for by a relatively large loaded area; (2) a central ("gage") region of relatively small loaded area where failure is meant to be produced, and; (3) a transition region joining the gage and grip regions. (A clear cut transition region, (3), is not present in many types of test specimen).

The gripping region is characterized by complex loading features, often involving very peaky stress distributions associated with hard contact points. Three dimensionality in the form of stress variations through the thickness is frequently present in the grip region. In the representative case shown on the following page, the load is introduced through the hard teeth of serrated surfaces of a wedge grip which results in through-the-thickness shearing; in the transition region this translates into spreading of the load in the lateral direction via in-plane shearing. Softening layers which may include tabs, thin sandpaper sheets or other approaches, may be present in the grip region. In beam-type specimens used for short beam shear and flexure testing, hard contact points represented by small-



Elements of Generic Test Specimen

radius rods of a relatively rigid material such as steel may be present that give rise to severe stress peaks in the load introduction region which are unrelated to the desired stress state.

The ideal mechanical property test specimen would provide a large effective loaded area in the grip region to compensate for stress peaks caused by the gripping arrangement, while allowing the stresses in the gage region to approach a uniform condition of high stress which ensures that failure takes place in that region. Furthermore, sufficient volume of test material should be involved in the gage region to provide an adequate sampling of the variability which is characteristic of the material being tested. For various reasons, such an ideal form of behavior is hardly ever achieved in practical test specimens for composite materials.

Specific problems which hamper successful mechanical property measurements in *organic matrix composites* will be summarized at this point.

Measurement of mechanical properties in organic-matrix composites is difficult because

of a general lack of ductile response together with large differences in the mechanical strengths of such materials for stresses in various directions. The problem is relieved somewhat for materials reinforced in more than one direction because the strength differences are considerably less in such cases, but the requirements of the technology are currently set by those for unidirectionally reinforced materials.

For the situation shown in the preceding Figure, for example, a metallic specimen will be relatively insensitive to the indentations caused by the serrations of the loading grips, and no special difficulty will be caused by the details of the transition region, since local yielding will cause the stress at any cross section to tend toward a uniform "P-over-A" value (i.e. nominal stress defined by load divided by section area) applicable to the section under consideration; these "P-over A" stresses will be obliged to have their maximum values in the gage region by the mechanics of the situation, specifically the fact that the smallest section occurs there, so that satisfactory confinement of failure to the gage region will be obtained. Accordingly, there is little need for concern over the possibility of not obtaining representative failures in metallic test specimens.

In the case of organic composites reinforced with high strength/high modulus fibers, on the other hand, achievement of representative failure is difficult. For example, it was found early in the development of the technology of advanced composites that for tension and compression testing, width-wise tapering to form a stress-focussing transition region (see the preceding Figure) usually leads to splitting failures in the tapered region long before a valid failure can be obtained in the gage region. This tendency appears to be related to excessively low shear strength of organic matrix composites in comparison with their tensile or compressive strength in the fiber direction. For the case of tension testing, the problem was dealt with in early efforts by the introduction of rectangular (i.e. uniform width) test coupons with thickness-wise bonded-on doublers (i.e. tabs) at the ends, through which the load was sheared in. This is generally accepted practice for tensile testing, as well as a number of compression test specimen designs.

On the other hand, the processes governing the behavior of the tabs lead to high stress peaks at the gage ends of the tabs, so that failures near or inside the tabs are quite likely and are commonly observed. Even though a consensus developed for the use of tabs, they obviously do not achieve the type of behavior described previously as the ideal of a test specimen design. Moreover, a number of practical difficulties are associated with tabs.

Debonding of tabs is certainly not unusual, and is especially troublesome for test situations involving high temperature and humidity. In other words, the use of tabs as a supposed cure for the problem of splitting in width tapered tension and compression specimens is not a completely adequate solution. This kind of poor choice of alternatives characterizes many situations in the testing of composites.

An additional complication is caused by the fact that designers of composite structures need a much larger variety of property measurements than those working with metals. In the latter case a single yield strength based on a tension test is adequate for predicting yield-related failure in tension, compression and shear loading, due to the fact that failure modes corresponding to various loading modes in metals can be traced back to the same yield condition through the use of Mohr's circle transformations. In composites, the design can generally not proceed without independent measurements of tension, compression and in-plane shear properties, both modulus and strength, as well as a number of other properties, each of which has a unique failure mode that cannot be inferred from other loading modes.

In addition to increased effort corresponding to the requirement for a greater variety of test measurements, special difficulties specifically associated with compression testing arise. These have to do with the fact that properties often have to be measured on thin-gage specimens which tend to be prone to Euler column buckling prior to valid compression failure of the test material.

Greater variability of fibrous composites is also a factor which leads to problems in mechanical property testing. Not only are structural metals produced from extremely mature technology, but they are formed in large lots of highly homogenized constituents, and uniformity of strength and modulus is to be expected with them. Composites are built up by mechanical placement of constituent reinforcement and matrix components using methods which cannot be controlled to nearly the same level of uniformity. Reflection of this variability in mechanical property test data is a legitimate result, but variability may also be an undesirable characteristic of the test method. Lack of consistency between test results obtained on the same lot of material from different organizations is a common occurrence.

FACTORS AFFECTING PERFORMANCE OF TEST SPECIMENS

In view of the above comments, certain specific issues can be cited as a basis for judging which of the current test methods are well in hand vs. which are in need of additional development effort. These include: (1) whether or not the test produces a valid failure mode; (2) whether the stress distribution in the specimen is such as to insure failure in the gage region as opposed to the development of spurious failures; (3) sensitivity of the test results to practical considerations such as specimen machining tolerances, specimen surface finish requirements and accuracy of alignment of the specimen in the test machine.

These issues are clarified in the following discussion.

Failure Modes for Various Types of Loading

Except for buckling in the case of compression specimens, spurious failures are usually the consequence of severe stress concentrations in the load introduction region. Some obvious examples can be stated.

Tabbed specimens tend to fail in many cases at the tab ends or inside the tabs. Stress analysis shows that stress peaks which occur there are unacceptably severe unless the tab ends are bevelled at angles as low as 10°. Failures in the tab bonds can be expected at high temperature and humidity because of the limitations of typical adhesives. Such failures may be less likely in compression testing because of the compressive nature of transverse extensional stress to which bond materials tend to be sensitive.

Many types of compression specimen are subjected to column buckling failure because of the need for thinness in the specimen. End loaded compression specimens often fail by "brooming", i.e. splitting apart of fibers near the loading platens. It is not clear that the mechanism of brooming is adequately understood.

Width tapered specimen shapes tend to fail prematurely because of shear stresses associated with the tapered portion. With cross-plied materials, however, width-wise tapering is somewhat more successful because the spurious stresses associated with tapering tend to be relatively lower and because the cross reinforcement tends to

strengthen the material against undesirable failures.

Beam-type specimens (flexure and short beam shear tests) tend to fail prematurely due to contact stresses near loading points which are non-representative of desired failure modes.

Status of Stress Analysis in Test Specimens

Stress analysis has been carried out for some width tapered specimens, which show that linearly tapered ("bowtie") shapes, as well as so-called "streamline" shapes give better performance that "dogbone" shapes such as the ASTM D638 specimen which was originally developed for plastics but has often been used for testing of composites. Comparison of analytical and experimental results have confirmed that the D638 is prone to failures at the end of the tapered region where the stresses are maximum.

Stress analyses of tabbed specimens have shown that severe stress peaks occur at the ends of the tabs, and that the use of bevelled ends on the tabs is probably not effective for tab angles greater than 10°. Linear elastic analyses of the effects of tab material indicate large differences in peak stresses for steel tabs vs. fiber glass tabs which are not necessarily reflected in test results. Ductility of the adhesive used to bond tabs, which probably has not been investigated analytically to date, may be a more important factor than the properties of the tab material.

A number of buckling analyses of compression specimens have been performed, which have given considerable guidance on requirements for avoiding premature buckling failures. Brooming which is a frequent problem in end loaded compression specimens is probably not well understood and needs further investigation. Sandwich beam compression specimens have been analyzed to examine the degree of restraint between the core and composite skin being subjected to compression testing.

Considerable stress analysis has been reported for shear test specimens. In the case of in-plane shear tests, stress analysis has been conducted on a number of specimen designs such as the ±45° tension test, the Iosepescu test, the rail shear test, the picture frame shear test, the double notched shear specimen and others. The double-notched shear specimen is a good example of a design based on an oversimplified concept of the stress state in the specimen which is not even approximately achieved in practice. Because of extremely high stress peaks in such specimens, all test results obtained from

them must be considered suspect. Stress analyses have also been performed on beam-type specimens such as the short beam shear test for transverse shear properties to determine the effect of stress peaks around the load points.

Specimen Machining and Alignment Effects

Machining tolerances for test specimens may be somewhat arbitrary. A rational basis for setting tolerances may be developed from parametric studies of the effects of specimen machining errors, i.e. computer modelling of the influence of non-planarity and non-paralellism of specimen surfaces on the stress state in the specimen. Such studies have been presented in the literature to some extent, especially in the case of compression testing where the concern for sensitivity of test results to specimen imperfections is generally prevalent. Specimen alignment is a crucial feature of many test methods, again, especially in the case of compression testing. Some testing jigs have provided special features for insuring precise specimen alignment. As in the case of machining tolerances, requirements for alignment are often specified arbitrarily, and there is a need for combined experimental and analytical studies to establish these requirements more rationally in several types of test.

FORMAT OF THE DOCUMENT

The preceding discussion illustrates the type of information that this report is intended to provide. Each of the 3 volumes a provides comprehensive review of most of the test methods which have been used for obtaining structural properties of composite materials over the years. These include most of the standard methods which have been adopted by ASTM, SACMA (Suppliers of Advanced Composite Materials Association) as well as other organizations, in addition to a number of methods which have become generally popular in the industry but have not been adopted as standards.

The format of each volume includes the following:

1. EXECUTIVE SUMMARY (constitutes a brief summary of the state of testing methodology for the type of testing addressed in the volume under consideration)
2. INTRODUCTION

3. SUMMARY AND RECOMMENDATIONS (includes a relative ranking of test methods in each category, and recommendations for effort needed to correct deficiencies)

4. DETAILED DISCUSSION (a detailed discussion of each test method under consideration, including: failure characteristics of the specimen; discussion of the status of stress analysis for the specimen considered and conclusions to be drawn about the effect of stresses on test results and; practical considerations such as sensitivity to machining tolerances, specimen alignment requirements, etc)

In addition, an appendix is included with each volume which contains an annotated bibliography covering all of the available literature back to the mid 60's which it was practical to review within the scope of this effort.

TECHNICAL SUMMARY

Test methods for determining tensile properties of fiber composites are reviewed based on the works listed in the Appendix. Based on the review, the following points appear noteworthy.

(i) Determination of the Young's modulus is not a serious problem and practically all of the methods should yield reliable results.

(ii) Although the straight sided coupon is not ideal, it is the only test which can be considered acceptable at this time. The ASTM Standard D3039 is currently being revised with due consideration to the experiences of a wide cross section of the composites community accumulated over a number of years. Additional studies for the purpose of improved tab designs and gripping arrangements appear worthwhile.

(iii) Dogbone, Bowtie, and Streamline specimens are not suitable for unidirectional specimens. However, these or other specimens based on the same concept (reduced gage section) should be useful for cross reinforced or fabric materials.

(iv) Further analytical, experimental and data correlational studies for cross reinforced specimens are needed, especially for the development of data reduction procedures which will be acceptable to the composites community.

(v) Alternative designs, such as thickness tapered specimens should also be investigated .

In summary, it can be concluded that straight sided specimens (revised ASTM D3039) may be considered tentatively acceptable at this time. However, studies are needed to improve the performance of the straight sided coupon and to develop an acceptable standard for cross ply testing.

1. INTRODUCTION

Valid axial tension testing of very strong unidirectional composites is a challenge to experimentalists. Since the unidirectional material is the basic building block in structural laminates, its properties must be well characterized for use as input data to lamination analyses. This philosophy is accepted by a majority in the composites community. For this reason considerable emphasis is placed on testing of unidirectional composites.

This volume describes the state of the art of tension test methods obtained from a literature search. Adequate gripping of the test specimen is the principal problem in tension tests. Load must be transmitted from the grips of the testing machine to the specimen via shear and the shear strength of a unidirectional composite is typically at least an order of magnitude lower than its axial tensile strength. Shear failure near the gripping region or damage of fibers under the grips are the most common problems. In addition, shear induced splitting may occur in imperfect specimens. For these reasons, considerable work has been performed with a goal to improve the performance of tension test specimens. In addition, a number of workers now favor the use of laminate testing to back out unidirectional properties. The Appendix contains an annotated bibliography of the works reported in literature. Many of the bibliographical entries are also directly referenced in the discussions presented in the report. These are marked with an asterisk in the list of references so that the interested reader can refer to the bibliography for more information. Description of different methods, discussions and recommendations are based solely on review of these works. No additional research was conducted for preparation of this report. An Executive Summary is given in the preceding section. The following section gives a detailed summary of the state of the art and identifies areas where additional effort is needed. For each test method, the following points are addressed in the Summary.

1. Problems associated with load introduction and free edges.
2. Uniformity of stress field.
3. Sensitivity of imperfections.
4. Acceptability of failure modes.
5. Simplicity and adequacy of data reduction schemes.
6. Specimen preparation and fixture requirements.
7. Consistency of results and other information.

For issues related to tabbing and cross reinforced specimens, important relevant points are discussed.

Detailed discussions of the following test methods and issues are given in the sections which follow. These discussions are appropriate for all fiber composite systems except where some characteristic differences for the specific material are noted.

1. ASTM D638 Type I ("Dogbone") Specimen
2. Straight Sided Coupon With or Without Tabs
3. Linear Tapered ("Bowtie") Specimen
4. Streamline Specimen
5. Issues Related to Tabbed Specimens
6. Testing of Laminates With Cross Reinforcements

The specimens listed in items 1-4 may be suitable for testing laminates. The sixth item addresses the issue of obtaining 0° properties from cross ply and other laminate tests.

For each of the test methods mentioned, the following issues are addressed.

a. GENERAL DESCRIPTION OF THE TEST METHOD - Description of the method and procedure in its commonly used form including drawings of specimens and fixtures.
b. STRESS STATES AND FAILURE MODES - General nature of the stress state, representative results from stress analyses (if reported), disturbances and stress peaks at critical locations like load introduction points (including effects of grips, tabs, fixtures and tab variations and problems in hot/wet testing). Common failure or damage modes and consistency of results are also addressed.
c. DATA REDUCTION - Data reduction procedure.
d. OTHER REQUIREMENTS AND MODIFICATIONS - Other considerations like specimen machining tolerance and alignment requirements, effects of minor imperfections (specimen, fiber geometry, etc.) and suggested variations of the method for improving specimen performance.

2. SUMMARY AND RECOMMENDATIONS

This section gives a summary of findings related to strength measurement (discussed in the following sections) followed by some recommendations identifying areas of further work. It may be noted that modulus measurement is not a serious problem. The summary for each test method follows the seven point outline defined in the Introduction. For tabbing and cross ply specimen relevant points are noted. Recommendations are given at the end of the section.

2.1 ASTM D638 TYPE I ("DOGBONE") SPECIMEN

1. Load introduction does not pose a problem because of larger width in the grip region.
2. Stress distribution is uniform in the gage section, but stresses peak in the transition region.
3. Sensitivity of unidirectional specimens to imperfection has not been established since strengths are low because of the stress peaks.
4. The specimen is not suitable for testing unidirectional composites, since failure usually occurs in the transition region.
5. Data reduction procedure is simple.
6. Careful machining is required in the transition regions.
7. The specimen appears to be adequate for cross reinforcements or for fabrics.

2.2 STRAIGHT SIDED COUPON

1. Specimens with tabs are commonly used. Issues related to tabbing are discussed later. If tabs are not used, surface layers may be damaged under the grips unless controlled hydraulic pressure is employed.
2. Stress field near tab termination is complex and stresses peak at that location.
3. Unidirectional specimens are very sensitive to misalignment. Even 1° difference may cause 30% strength reduction.
4. Failure initiation near tab termination or splitting due to misalignment can occur and such modes are not acceptable.

5. Data reduction procedure is simple.
6. Utmost care is needed to avoid misalignment in unidirectional specimens. Uniformities in thicknesses of specimen and tabs are required, otherwise eccentric loading may cause bending of the specimen and higher interlaminar stresses under tabs.
7. The test is not perfect but with proper specimen preparation, tab design and adhesives, some consistency in test data has been reported and this is the only test which is considered acceptable for unidirectional materials. Performance of cross ply specimens has been found to be better, since they are less sensitive to imperfections.

2.3 LINEAR TAPERED ("BOWTIE") SPECIMEN

1. Load introduction does not pose a problem because of larger width in the grip region.
2. Stress peaks exist at the edges where the test area and the tapered regions meet.
3. Sensitivity to imperfections has not been established, but misalignment is likely to be critical.
4. Failure mode for unidirectional materials is usually not acceptable, since failure initiates as splits near the stress peaks.
5. Data reduction procedure is simple.
6. Utmost care in preparation of specimen edges is needed for unidirectional specimens.
7. Cross reinforced specimens with side slopes less than 5% and prepared with utmost care (near edges) have been found to be satisfactory. However,length required is large.

2.4 STREAMLINE SPECIMEN

1. Load introduction is not a problem because of larger width at the grips.

2. Although the specimen is designed to have low shear stresses, comparatively large lengths are required to have ideal unidirectional specimens.
3. Sensitivity to imperfections has not been established, but misalignment is likely to be critical.
4. Even with ideal specimen design, splitting from the edges can be very critical for unidirectional specimens. It is very difficult to avoid such splits even with utmost care (inclusive of polishing the edges) in specimen preparation.
5. Data reduction procedure is simple.
6. Specimen preparation needs numerical machining or special templates.
7. Satisfactory results can be obtained for cross reinforced specimens with moderate lengths and such specimen designs have been found to be attractive for hot/wet conditions and fatigue loading.

2.5 ISSUES RELATED TO TABBED SPECIMENS

1. Tab region failures are quite common due to stress peaks near tab ends. They are more severe for hot/wet conditions and fatigue loading. Debonding due to interlaminar stresses and fiber breaks due to elevated axial stresses are often noticed. Peak stresses can be reduced by using compliant (± 45 glass/epoxy) tabs with low taper angles (7° - 10°) as well as zero cut off thickness. However, special care is needed for bonding tapered tabs.
2. Bonded tabs or unbonded friction tabs without taper but compressed fully under the grips have been suggested to avoid tensile peel stresses, but shear stresses are increased and further studies are needed to determine usefulness of such tabs. Hydraulic grips are necessary when using unbonded tabs.
3. Better adhesives may prevent tab debonding and in some studies reasonable strength values have been reported in high as well as low temperature testing especially with cross reinforced specimens.
4. Use of hydraulic grips with controlled pressure (and servo-feedback hydraulic system) may reduce damage of surface layers in specimens with or without tabs. Wedges of such grips with less severe surface texture have also been

suggested especially with untabbed specimens, but no data are reported regarding its usefulness.

2.6 TESTING OF LAMINATES WITH CROSS REINFORCEMENTS

1. Tension tests on cross reinforced specimens to back out 0° strength are not very sensitive to fiber misalignments.
2. More data are needed for standard graphite and glass fiber reinforced thermosets. Modification of data reduction procedure may be needed for glass/epoxy systems.
3. Effects of scissoring on data from (0/±45) layup need some study.

2.7 RECOMMENDATIONS

Experimental Work

Straight sided coupon specimen is widely used in industry. However, stress concentration near tab ends (especially for unidirectional materials) remains as a serious problem. Although the specimen is not perfect, it is advantageous from the point of view of specimen preparation and it performs better than all other specimens for unidirectional composites. Since it has been shown that use of cross ply reinforcements can alleviate some problems associated with fiber misalignments, comparative studies should be performed with carefully prepared unidirectional specimens as well as cross reinforced ones. Some suggestions for such a study are given below, which should be conducted with commonly used graphite/epoxy and glass/epoxy specimens (since not much data are available for such materials for direct comparison) and other new composites with various alternative tab designs suggested in literature.

The following specific recommendations are made.

(a) Straight sided coupons with ±45° glass fabric, 7°-10° tapered tabs and zero cut off thickness.

(b) Straight sided coupons with bonded tabs (no taper) but fully compressed inside the grips.

(c) Straight sided coupons with friction tabs (no taper) but fully compressed inside grips.

(d) Untabbed straight sided, bowtie and streamline type specimens (last two for cross ply materials only) with special hydraulic grips (smooth to moderately textured faces on emery cloth) and controlled pressure.

(e) Some straight sided specimens with $0/\pm45$ layups.

(f) Monitoring ply crack densities in cross ply specimens, determine differences near free edge and inside the specimen as well as careful observation of failure modes are necessary.

(g) Some fatigue and hot/wet testing studies are also desirable.

In addition to studies on cross reinforced specimens, exploratory studies should also be made for the development of new alternative specimen designs, which may include thickness tapered specimens (by co-curing additional layers and machining) without or in conjunction with width tapering.

Studies to select pressure levels required for testing specimens with no tabs or friction tabs also appear worthwhile with careful observation of damage modes at grip zones. Use of wedge grips and hydraulic grips with standard and newly developed gripfaces (like ceramic particle coated ones) should be employed in such studies.

Effects of ductility and toughness of adhesives on performance of tabbed specimens should also be investigated.

Analytical Studies

Analytical studies for cross ply specimens are needed for the development of acceptable data analysis procedures. Good analysis models, which can consider ply cracking in laminates, are now available for this purpose. It may be noted that linear analysis may work well with some materials like high modulus graphite/epoxy, but it may not be accurate for others like glass/epoxy.

Analytical models should also be employed for making preliminary selections from an infinite number of choices for new specimens, tab and grip designs (including bonded and friction tabs and thickness tapered specimens). Such analyses will also be useful for making some decisions regarding appropriate thickness and types of adhesives.

Analytical investigations for studying the effects of adhesives with different amounts of ductility and toughness on the stress fields in tabbed specimens may be useful before experimental studies are performed with such adhesives. Number of tests required for an experimental investigation can be minimized based on the analytical results.

3. DETAILED DISCUSSIONS

3.1 ASTM D638 TYPE I ("DOGBONE") SPECIMEN

3.1.1 General Description of the Test Method

The gripping areas in this specimen are made wider than the test section and gradual transition zones (in the form of circular arcs) are introduced for changing the width (Figure 1). An ASTM Standard (D638) [1] exists for testing sheet, plate and molded plastics. The method has been found to work well even for randomly oriented whisker reinforced composites. However, for testing of fiber dominated materials (unidirectional, laminated or oriented whisker composites), it does not provide a satisfactory tension test method as discussed later.

3.1.2 Stress States and Failure Modes

Stress state in the gage section is uniform. However, stress peaks exist in the transition regions. Distribution of axial and transverse stresses near the edges (0.25" from the center line) in a glass/epoxy material (with 78.5% 0° and 21.5% 90° layers as reported in [2] is shown in Figure 1. It may be seen that the axial stress is highest near the start of the test section zone, whereas the shear stress reaches its peak value (> 0.1 times the nominal axial stress in the test section) closer towards the end zones.

Typical specimens with some cross reinforcements show fiber popping due to axial stress peaks near the edges close to the test area followed by axial cracking due to shear close to the end zones (Figure 2 [2]). These damages are often constrained in presence of some cross reinforcements, but may influence final failure at slightly higher loads. The use of the computed stress concentration factor may yield a measure of strength [2]. For unidirectional composites, straight splits usually develop and significantly lower the tensile strength. Failures near the shoulder have been observed in woven composites [3] and changing the shoulder radius (3" to 18") does not yield any significant improvement in strength. Use of tabs in the end zones has also been attempted but the results show large scatter [4] and no conclusion can be reached regarding their usefulness.

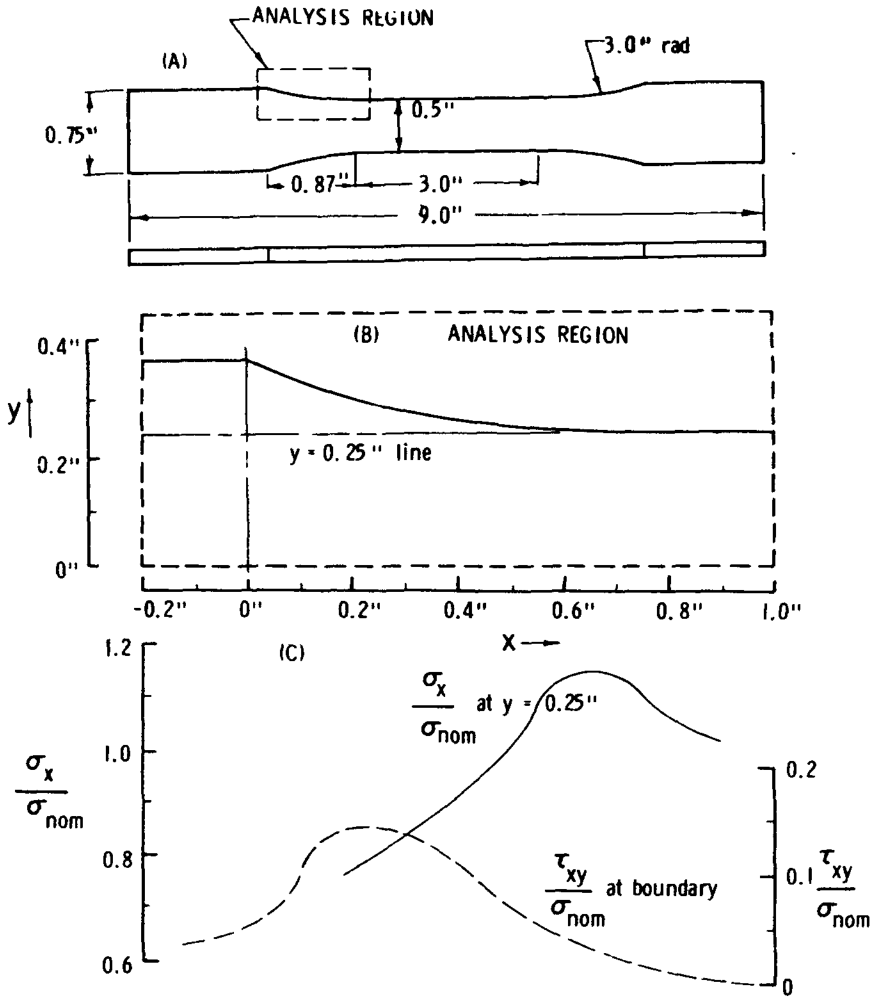


Figure 1. ASTM D638 Type I ("Dogbone") Specimen and Stresses [2]

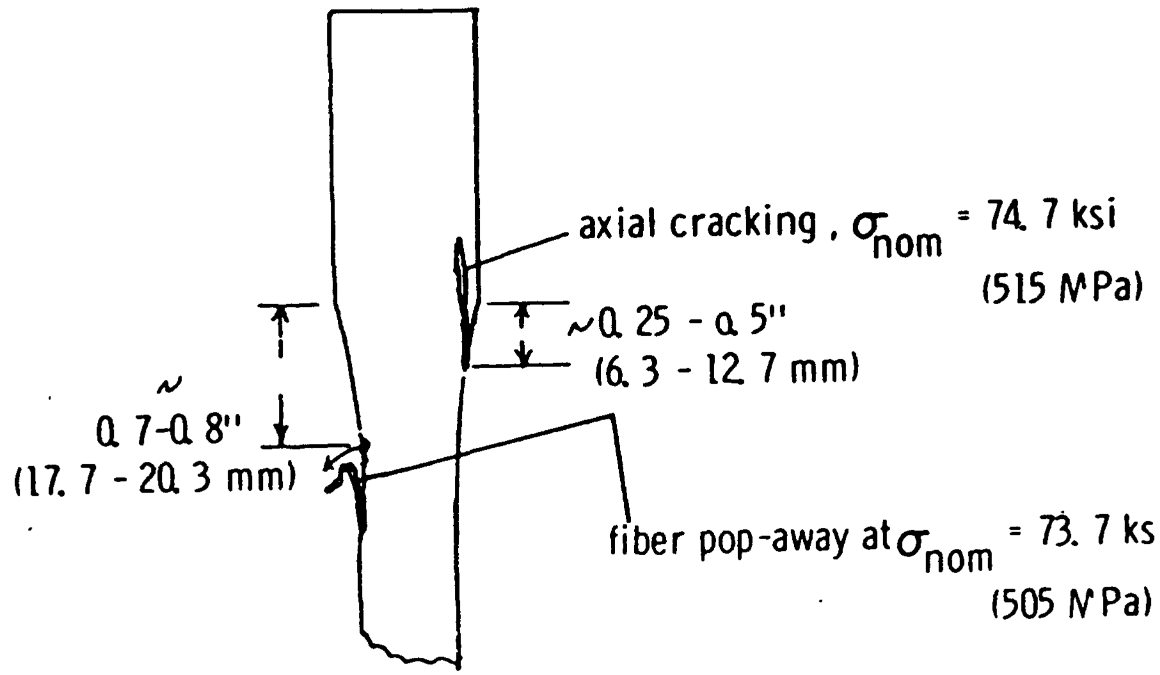


Figure 2. Typical Failures in "Dogbone" Specimen With Some Cross Reinforcements [2]

Since the test is not satisfactory for unidirectional as well as laminated composites, there is not much information available to judge the consistency of results from different sources. Hot/wet testing does not pose any special difficulty since no tabs or adhesive bonding are required.

3.1.3 Data Reduction

Data analysis is simple and straightforward.

3.1.4 Other Considerations and Modifications

Modulus and measured strength will obviously be affected by fiber or specimen misalignments and machining imperfections. Scored or serrated grip surfaces as well as other modifications are suggested in ASTM Standard D638 to prevent slippage at the grips. Modifications of the specimen have been attempted by changing shoulder radii or other geometric parameters but without any success.

3.2 STRAIGHT SIDED COUPON

3.2.1 General Description of the Test Method

ASTM Stardard D3039 [5] is commonly followed in industry. The specimen is a straight sided coupon cut out from a laminate without or with tabs (Figure 3). Commonly used specimen thicknesses vary from 6 to 24 plies. Widths of ½" for unidirectional materials and 1" for laminates are commonly employed. Suggested gage length is 5". Use of soft (± 45 fiber glass) tapered tabs feathered at the test section is preferred by many investigators [2, 6, 7 - 10]. Tabs may not be needed under certain circumstances (frictional devices like emery paper may be used to avoid slippage) and the ASTM Standard is now being revised to allow testing without tabs. However, in commonly used composites with load bearing 0° plies on the outer surfaces, fiber damage is often found to occur under the grips when tabs are not used. Effects of tabs are discussed in detail in a later section. Axial and transverse

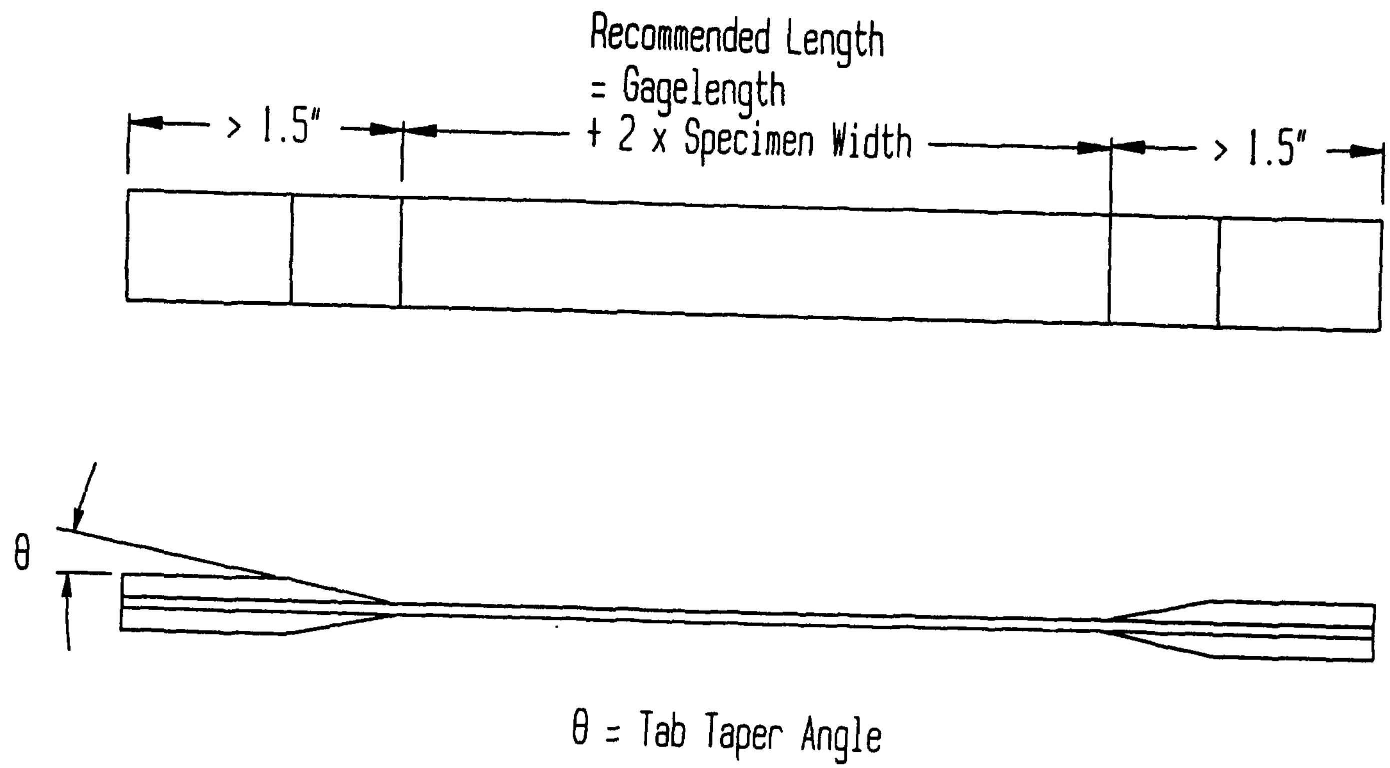


Figure 3. Straight Sided Coupon Specimens, see ASTM D3039-76, Reapproved 1982, under revision [5] for details.

(for Poisson's ratio measurement) strains are measured. Alignments should be checked with back to back and side to side to gages, which should indicate bending effects, if any.

3.2.2 Stress States and Failure Modes

Uniform axial stress exists in the test section, when there are no alignment problems and bending effects. Stress states are, however, quite complicated under the tabs (or under grips when no tabs are used). Finite element studies have been conducted to determine optimum tab configurations [2, 7 - 9, 11]. Some representative stress distributions in a cross ply specimen [2] for varying taper angles (Figure 4) are shown in Figure 5, which shows that shear and transverse (through the thickness) stresses are high at the tip of the bevel and the axial stress is also magnified. A stress singularity exists at this point in the ideal elastic case. The stress peaks are reduced when lower taper angles are used. Such stress predictions must be taken with reservations, however. Results obtained [2] for $0_{10}/90_4$ E glass epoxy laminates showed little clearcut difference for 10°, 30° and 90° tab bevel angles. The use of right angled tab ends (i.e., 90° bevels) has the obvious advantage that both clamping pressure during tab bonding and grip pressure during testing can be maintained to the end of the tab, which may override the effect of a stress singularity at the tab ends. In addition, tests on 10° tabbed specimens reported in [2] indicate that maintaining clamping pressure out to the end of the bevel during tab bonding may have a significant effect on tab performance, and that failure to provide such clamping may counteract expected advantages of low bevel angles. Applying such clamping pressures to more steeply bevelled tabs may be difficult.

Some possible failure modes are shown in Figure 6, first two are common and acceptable in fiber dominated layups. Straight break across width can occur in 90° coupons or in specimens with little 0° reinforcements. Edge delaminations may develop in some cross ply laminates. Tab region failures are often observed in fiber dominated layups, details of which [2] are shown in Figure 7. Most of the tabbed specimens tested in [2] failed under the tabs or close to the end of the bevel. Tab debonding and fiber breaks inside the tabbed region caused by clamping pressure were noticed. Strengths obtained with square (90°) tabs were found to be higher than those obtained using 30° tapered tabs and in some cases with 10° tabs, possibly due to tab debonding in the latter specimens. Strengths are, however, higher (than those from 90° tabs) when special care (clamping tab ends) is taken to bond the 10°

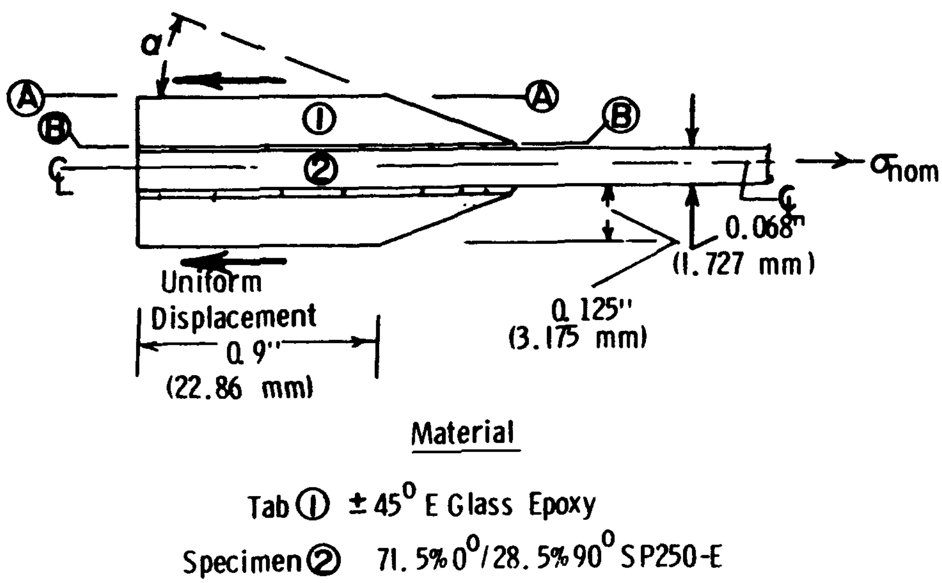


Figure 4. Tabbed Specimen Model Assumed in Stress Analysis [2]

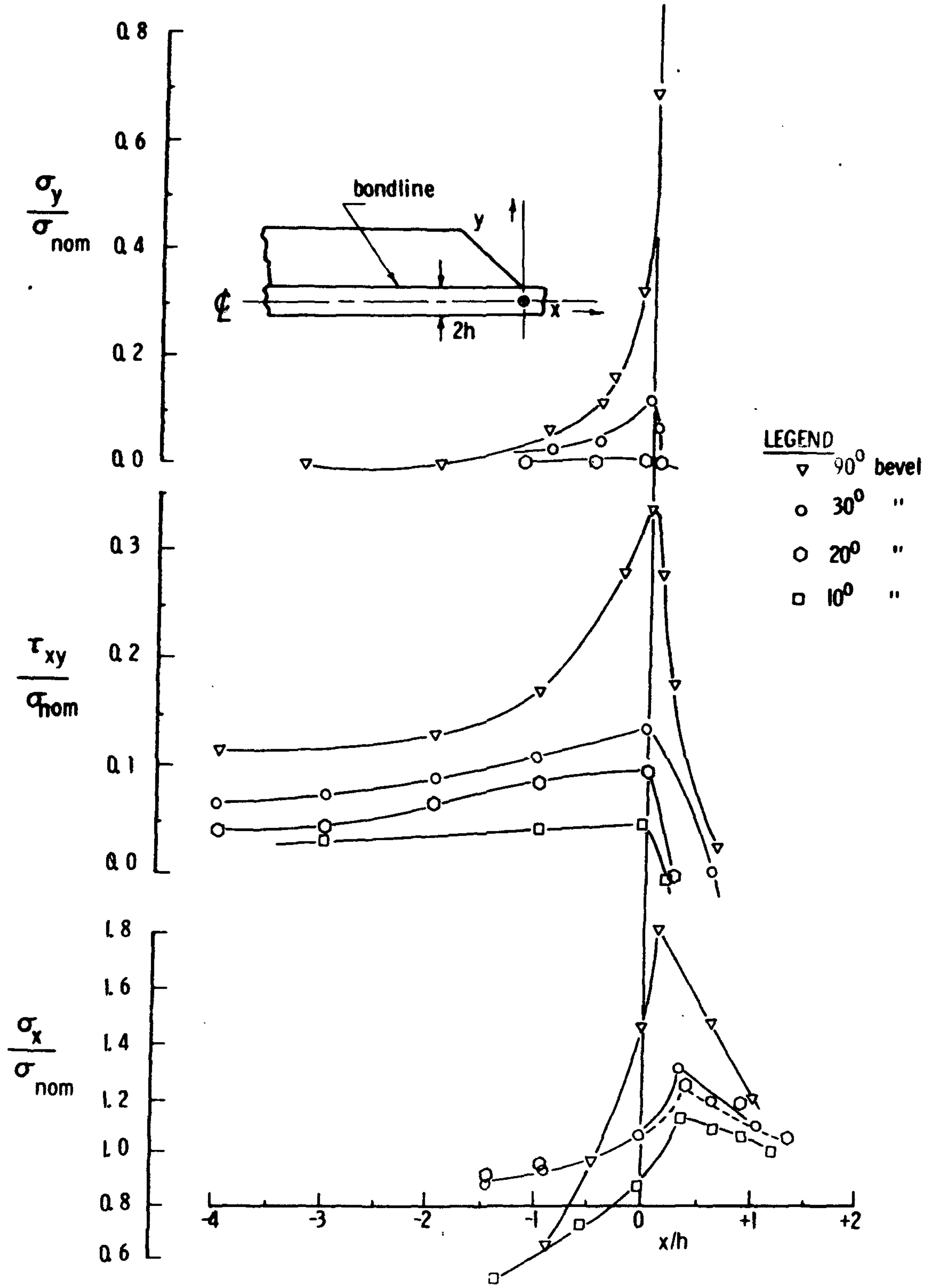
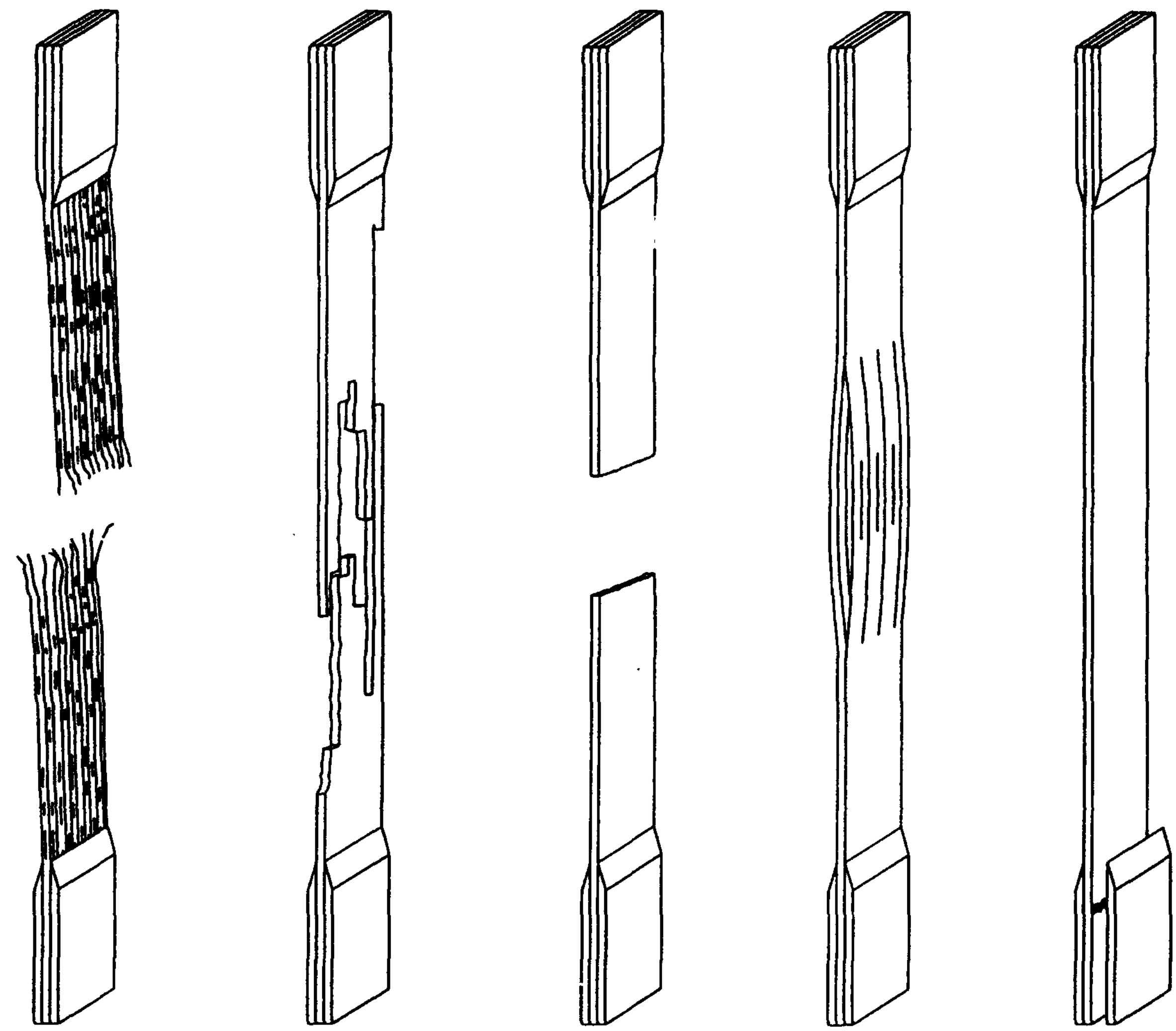


Figure 5. Theoretical Stresses in Tabbed Specimens [2]



Shattered (Acceptable & common in unidirectional specimens)

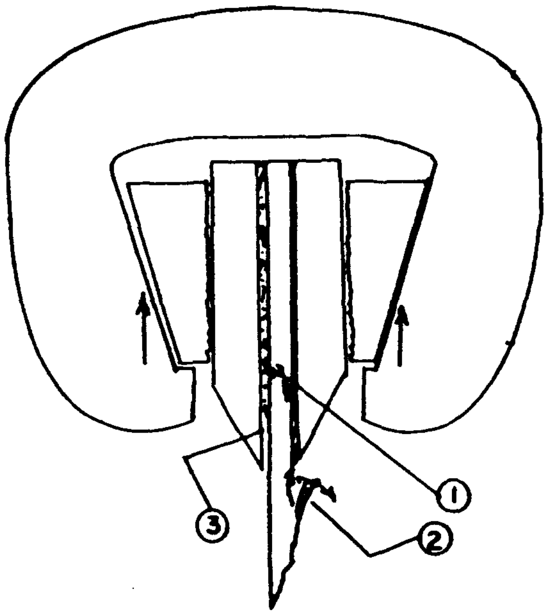
Failure with Splits (Acceptable & common in unidirectional specimens)

Clean Cut (Acceptable & common in 90° or 90° dominated layups)

Edge Delamination (May be found in crossply layups, unacceptable)

Failure Near Tab End (Unacceptable)

Figure 6. Possible Failure Modes in Straight Sided Coupon



Tabbed Specimen Failures

1 fiber break between tabs, especially at end of grip region

2 fiber breaks outside tab region near end of bevel

3 tab de-bonding

Figure 7. Typical Tab Region Failures [2]

tapered tabs. Therefore, special care in bonding is required when using tapered tabs [10]. Hot/wet testing is a serious problem with tabbed specimens since a majority of failures occur in or close to the tabbed area [6, 12]. Difficulties are also encountered in fatigue tests [9, 12] due to generation of heat during testing. A detailed discussion of issues related to tabbed specimens is given in a later section.

Reasonably consistent results can be obtained if extreme care is taken [13] in specimen preparation (discussed next) and tab bonding.

3.2.3 Data Reduction

Data reduction is simple and straightforward.

3.2.4 Other Considerations and Modifications

Eccentric loading increases the stress peaks in the tabbed regions [8] (in addition to causing bending stresses in the regions). Such loading may result from differences in tab thickness as well as variations in specimen thickness. Tolerances for those two quantities should be $\pm 1\%$ and $\pm 4\%$, respectively, as prescribed in the ASTM Standard under revision. Severe thickness variation in a group of specimens can cause difficulties in data reduction. Use of strength per ply or a nominal thickness ((in place of measured) is recommended for such cases [6, 12].

Misalignment of fibers in unidirectional specimens can cause severe reduction in strength as well as modulus [14, 15]. Specimens cut with 1° misalignment develop slits parallel to fibers, reducing effective load bearing area significantly (Figure 8) because of the large length to width ratios [16] and causing as much as 30% reduction in strength [15]. This is a major problem in testing of unidirectional composites and it can be avoided with special care in finding the fiber direction and specimen preparation [13]. Use of cross ply testing has been suggested by many investigators [16 - 18, 13, 19] to avoid this problem.

Proper machining and polishing of the straight edges have been found to increase the strength especially in unidirectional specimens. In addition, some testing facilities prepare specimens by breaking them along lines parallel to fibers to insure that the edges do not cut fibers.

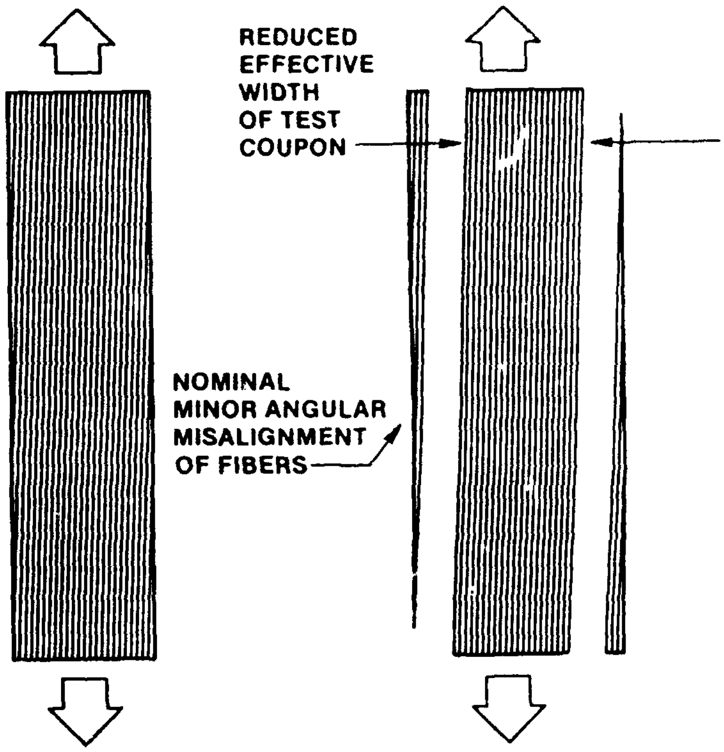


Figure 8. Effect of Misalignment in Unidirectional Specimens [16], Copyright ASTM and Douglas Aircraft Co., Reprinted with Permission.

3.3 LINEAR TAPERED ("BOWTIE") SPECIMEN

3.3.1 General Description of the Test Method

In this specimen a ½" wide x 2⅛" long test section is gradually (linearly) expanded to a wide area under the grips [3] avoiding the use of tabs. A smooth transition from test section to side sloped region is desirable (¼" radius). It was designed to solve the stress concentration problems associated with the dogbone specimen and the failures in the tabbed regions of the tabbed straight sided coupons. It has been reported that strengths of woven composites obtained from these specimens with side slopes of 2.6% are equal to or higher than dogbone or tabbed specimens [3].

3.3.2 Stress States and Failure Modes

Finite element results for a (0/90) laminate with 71.5% 0° and 28.5% 90° layers and side slopes of 5%, 10% and 12.5% [2] show that stress peaks exist at the point where the test section ends and side slopes begin (Figure 9). The peak value shown is, of course, the average stress in the elements located at that point. In any event, the severity of stress concentration decreases with decreasing slope and possibly for this reason test results reported in [3] are higher or comparable to those obtained from dogbone or tabbed specimens. It is reported in [3] that failures were usually in the test section. In [2] specimens with taper angles greater than those in [3] (side slopes of 5% to 12.5%) exhibited failures in the form of shear cracks near the point of highest stress values. Use of stress concentration factors (Figure 9) show that corrected values of strength are comparable with those from dogbone specimens with appropriate corrections. 0° bowtie specimens used in [20] showed considerably lower strength (30%) than tabbed straight sided coupons and slightly lower values (10%) as compared to streamline specimens. Cross ply bowtie strengths were comparable to those from streamline specimens, but slightly higher than those from tabbed straight sided coupons. All 0° bowtie specimens showed significant amount of splitting (starting at 60% of ultimate), which became catastrophic just before final failure. On the other hand, the splits in cross ply specimens were constrained as observed in [2] (Figure 10).

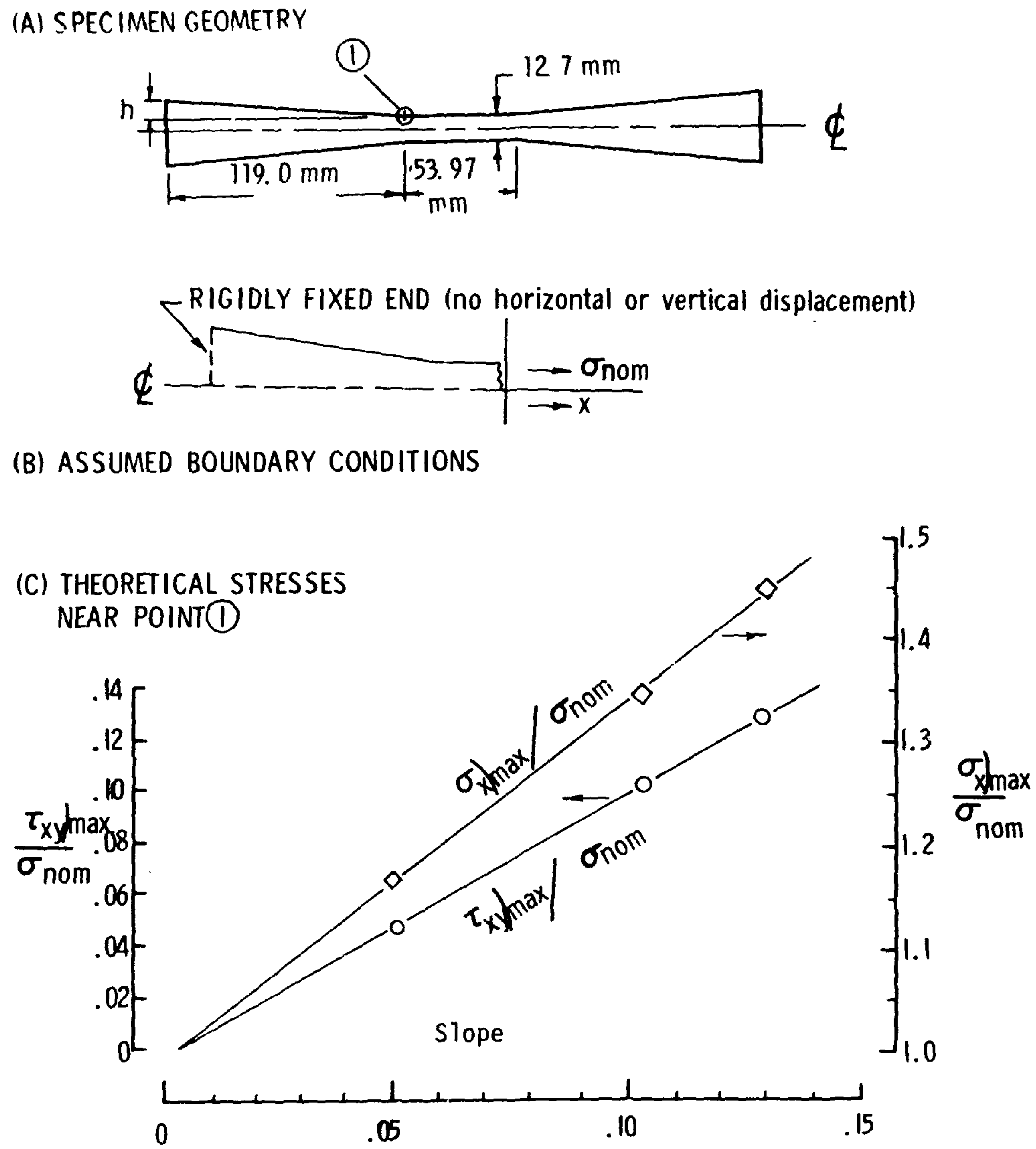
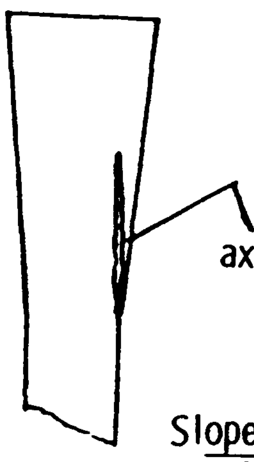


Figure 9. Predicted Maximum Stresses in "Bowtie" Specimen [2]



Slope, %	Ultimate Stress for First Failure ksi	Ultimate Stress for First Failure MPa	Nominal Ultimate Stress ksi	Nominal Ultimate Stress MPa
5.0	73.3	505	76.0	524
10.0	55.6	383	72.8	502
12.5	35.1	242	65.6	452

Figure 10. Failure Characteristics of "Bowtie" Tension Specimens, Constrained Cracking in Presence of Cross Reinforcements [2]

Hot/wet testing is not a problem since no tabs or adhesives are required. Sufficient data are not available to conclude anything about consistency of results.

3.3.3 Data Reduction

Data analysis is simple and straightforward.

3.3.4 Other Considerations and Modifications

Accurate machining of the specimens is required. Strength will obviously be affected by fiber misalignments as in straight sided coupons (discussed in the previous section). Several modifications by changing the side slopes have been attempted, but they are not satisfactory for unidirectional materials. The test may yield acceptable results for cross ply layups with low values of side slopes ($<5\%$).

3.4 STREAMLINE SPECIMEN

3.4.1 General Description of the Test Method

The use of streamline shapes (named after the analogy between hydraulic flow and elastic stress field) has been attempted in the past to reduce stress concentration in machine components. It has been extended in [2, 12] to obtain shapes of orthotropic tensile specimens so that the peak shear stress is kept at a low level and there is no magnification of the axial tensile stress. Large values of expansion ratio (ρ = width at grip area/gage section width) are desirable, but they tend to produce long specimen designs. For a chosen value of ρ, various specimen boundaries may be chosen corresponding to different streamlines characterized by a parameter γ (between 0 to 1). There is no magnification of axial stress when $\gamma < 0.5$ and shear stress peaks are reduced by choosing lower values of γ (Figure 11). Reasonable specimen dimensions can be obtained for $\rho = 1.5$ to 2 and $\gamma = 0.3$ to 0.4. For cross ply layups, lengths of the order of 12" are required for a test section width of 0.5". Some practical specimen shapes obtained by using circular arcs to blend streamline

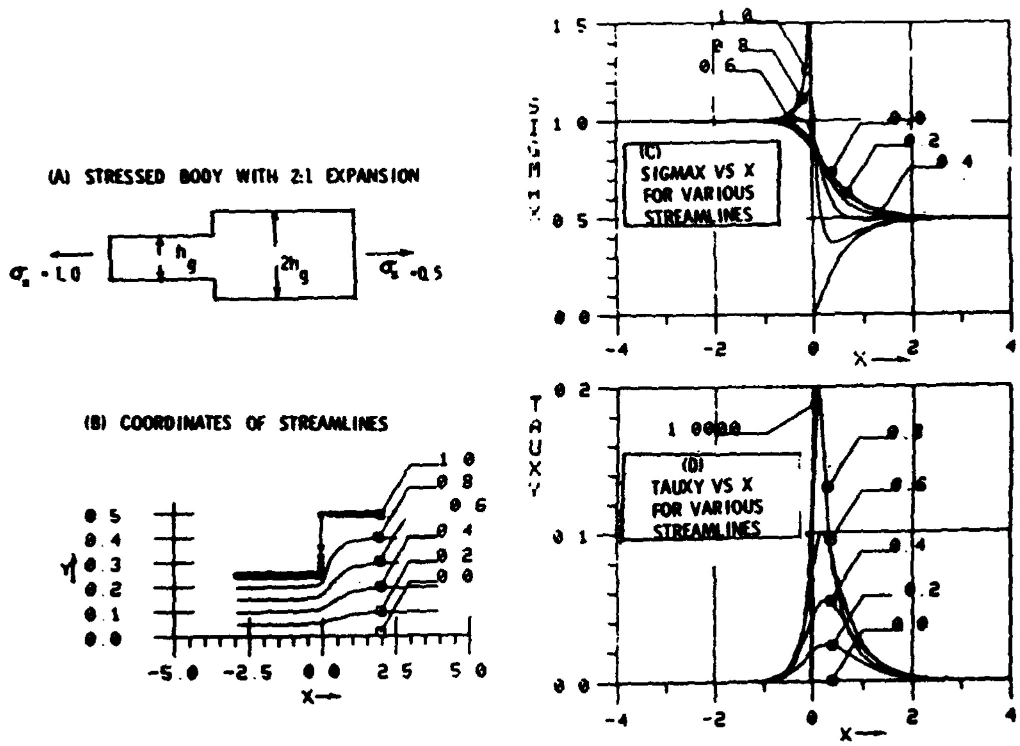


Figure 11. Stresses Predicted by Approximate Theory for 2:1 Expansion [12]

shapes to uniform width segments are shown in Figure 12. For unidirectional materials with high axial modulus and low shear modulus, longer specimen lengths ($\geq$24") are required to keep shear stresses at low levels. Tests are usually conducted without any tabs.

3.4.2 Stress States and Failure Modes

Stresses in a specimen obtained from approximate streamline theory are compared in Figure 13 with finite element solutions. The results show that transverse stresses are negligible and axial and shear stresses are well predicted by streamline theory.

As with the bowtie specimen discussed in the previous section, inclined surfaces of high modulus composites are excessively flaw sensitive. Figure 14 shows the results obtained from 12" long cross ply SL3 specimen shapes (Figure 12) made by using fine and coarse cutters as well as those from tabbed straight sided specimens [12]. It may be seen that fine cutting tools are required to obtain strengths higher than those from tabbed specimens. Similar results are reported in [20]. It may be noted that splitting is often found to occur in unidirectional specimens (as discussed in previous section on bowtie specimens) and strengths are usually lower than those from tabbed straight sided coupons [20]. Failure locations in cross ply streamline specimens are inside or close to the gage section area [12], whereas unidirectional materials may often fail away from the gage section near the splits, which develop [20].

Hot/wet testing does not pose a problem since tabs are not required. There is not much data to reach any conclusion regarding consistency of results from different sources.

3.4.3 Data Reduction

Data analysis is simple and straightforward.

3.4.4 Other Considerations and Modifications

Conventional machining techniques cannot be used to cut a specimen with a streamline shape. Preparation of templates and the use of special cutting machines or template guided routers are required. Machining should be very accurate and done with fine cutting tools as

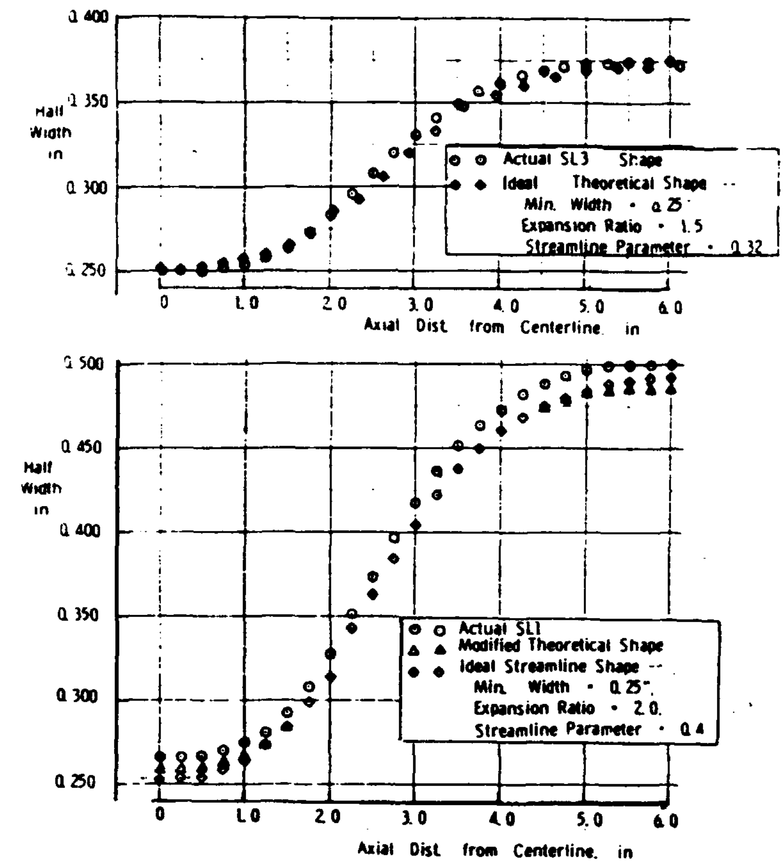


Figure 12. Theoretical Versus Practical Streamline Shapes [12]

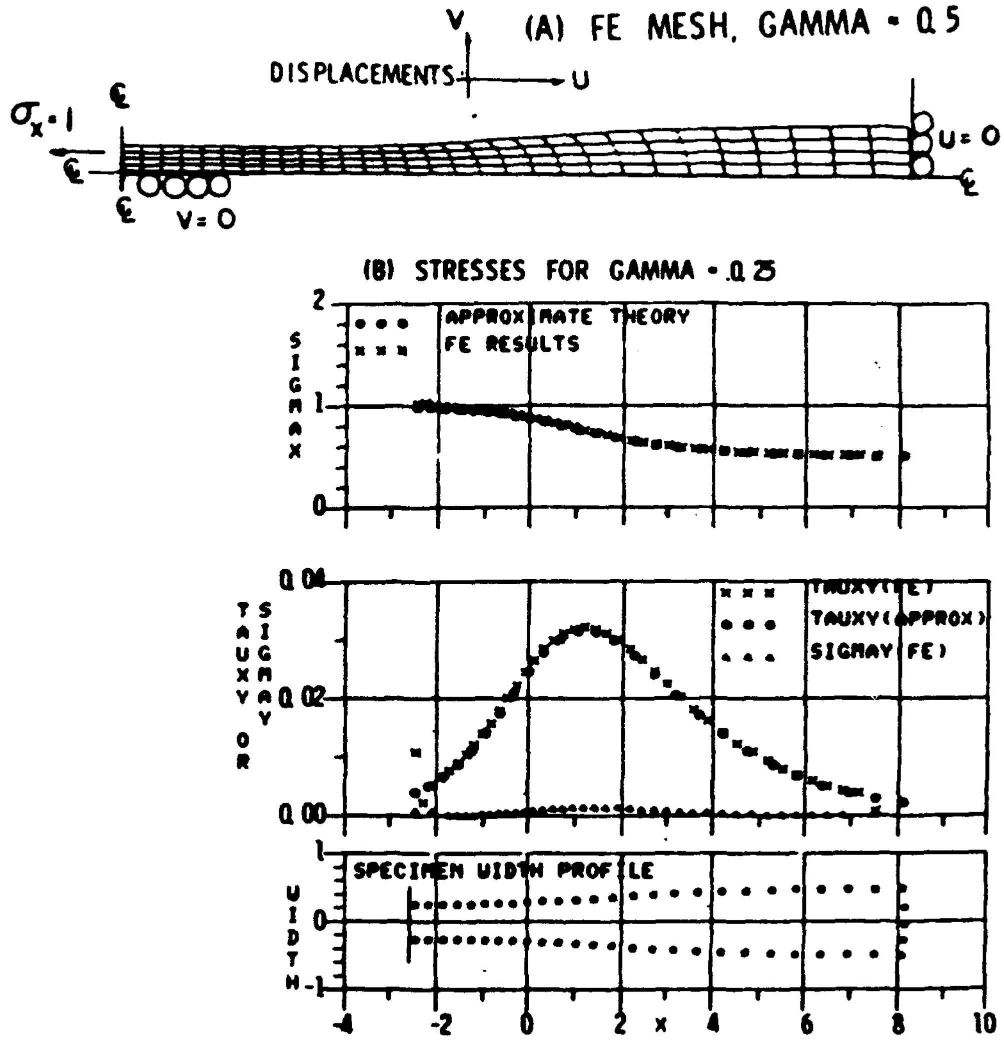
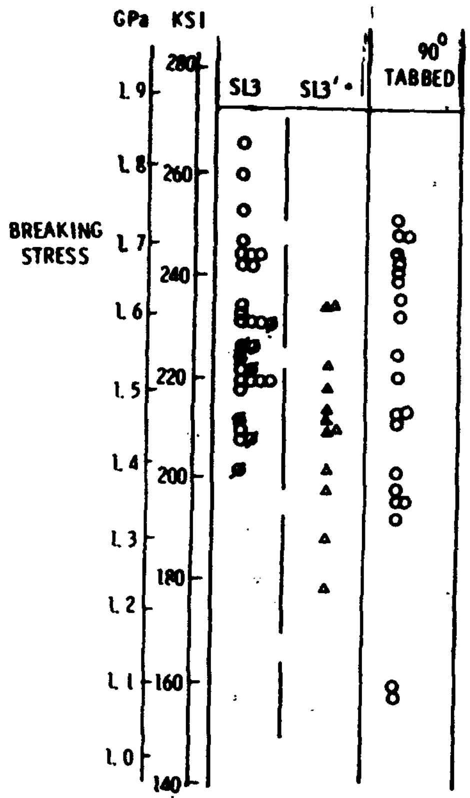


Figure 13. Comparison of Approximate Analysis with Finite Element Results [12]



SUMMARY OF TEST RESULTS

	SL3 STANDARD	SL3 COARSE CUTTER	90° TABBED
NO. OF TESTS	30	12	20
AVE (GPa)	1.59	1.45	1.50
COEF. OF VAR. (%)	6.6	7.8	12.4

*SL3' -- SL3 specimen machined with coarse cutting tool

ϕ -- specimens machined on TENSILCUT with fine cutter. Open circles represent specimens cut on AMMRC pantograph

Figure 14. Results for Tabbed and Streamline Specimens: Unidirectional T-300 5208 [12]

discussed earlier. Polishing specimen edges may be useful in improving performance of streamline specimens. It is not clear whether improved specimen machining techniques will yield better streamline specimens for unidirectional materials. However, such specimens are useful for testing cross ply layups especially for hot/wet and fatigue testing.

3.5 ISSUES RELATED TO TABBED SPECIMENS

3.5.1 General Comments

Tabs are required in testing unidirectional specimens and although many investigators are suggesting that straight sided cross ply coupons be used to back out unidirectional strength properties (as discussed in the next section), it appears that tabs are needed even with such specimens to avoid damages in the surface plies unless controlled hydraulic pressure is used for gripping. This section gives a summary of results reported in literature on various issues related to tabbed specimens. High frequency of tab region failures (especially for hot/wet testing) is discussed next followed by tab geometry and material effects.

3.5.2 Tab Region Failures

Current ASTM Standard D3039 which applies to tabbed specimens suggests that no failure should occur within one specimen width of each tab. Improper tab designs may result in frequent tab region failures (as high as 80% [7]). Figure 15 shows the distribution of specimen break locations in two tabbed specimens (30° and 90° tapered glass/epoxy tabs) of a cross ply material along with those in streamline and dogbone specimens [12]. It may be seen that 50% of 30° tapered specimens and 30% of those with no taper (90°) have to be rejected if the ASTM Standard is followed. Similar data for woven Kevlar/epoxy laminates (tested at three organizations A, B and C) at 0% and 95% relative humidity [12] are shown in Figure 16. It is clear that at higher humidity, tab or tab region failures can be very severe and most of the data have to be discarded. Such failures can be attributed to the stress peaks near tab ends and problems in the adhesive bond (and/or mismatch of properties of laminates and tabs) at high humidity condition. Similar effects are expected at high temperature or under fatigue. Figure 17 illustrates how measured strengths are lowered

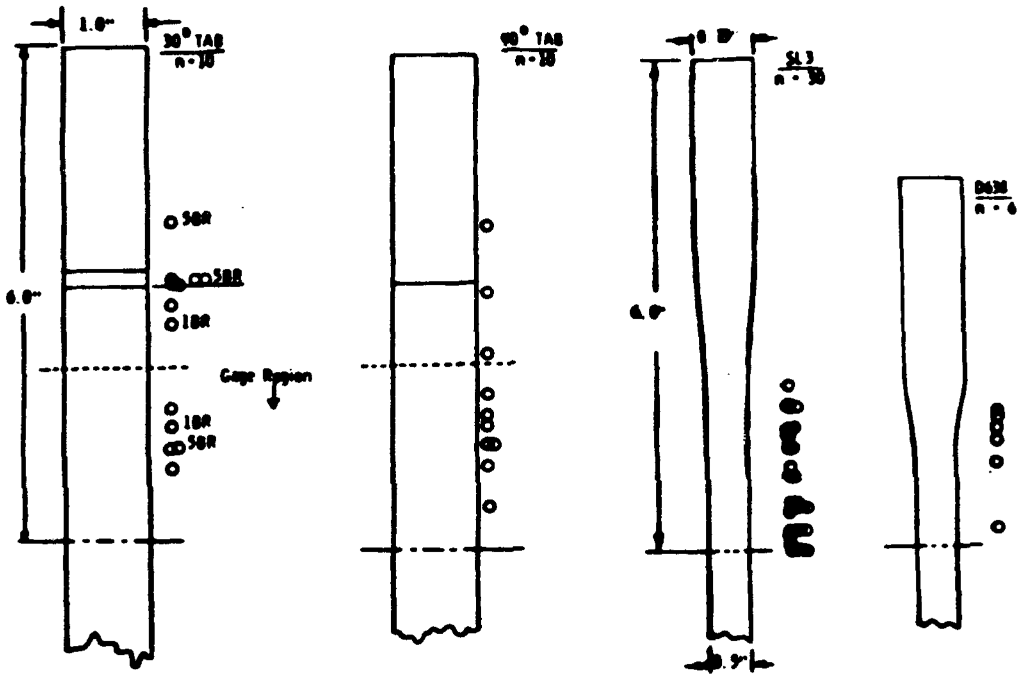


Figure 15. Specimen Break Locations in Cross Ply T-300 5208 Graphite/Epoxy Tension Tests [12]

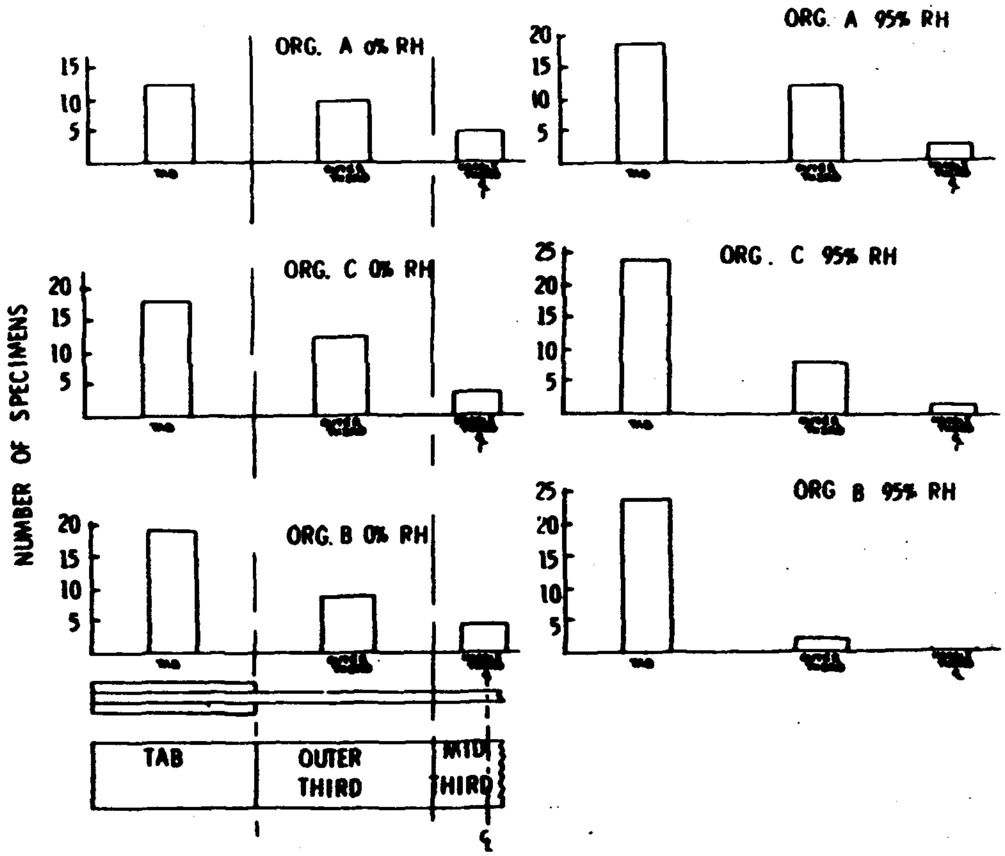


Figure 16. Failure Location Distribution in Tabbed Specimens - Woven Kevlar Epoxy Laminates [12]

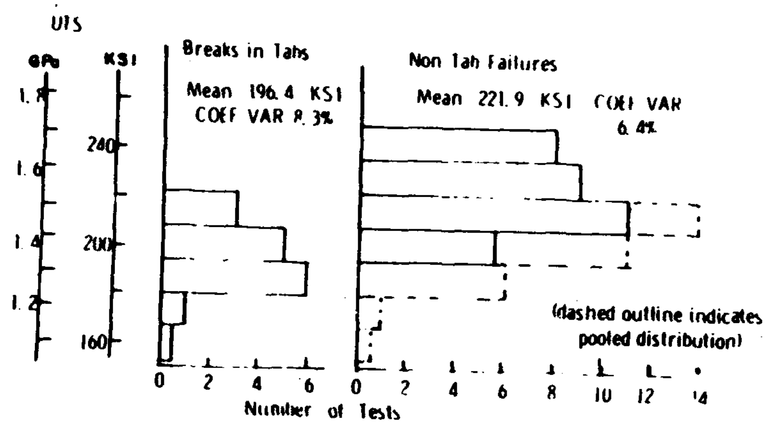


Figure 17. Effect of Tab Failures on Test Results: 14-Ply SP250 S-Glass (75°F. 50% Relative Humidity. 3-Month Exposure) [12]

because of tab failures in glass/epoxy material exposed to 50% relative humidity after 3 month exposure [12].

It is likely that the detrimental effects of hot/wet conditions (or long term exposures) may be reduced to some extent by using improved adhesive materials, but they can not be avoided because of the existence of stress peaks. It may, however, be noted that the problem may be less severe in cross ply tests as reported in [18], where good strength data are reported over a temperature range of -65° F to 180°F for a thermoplastic material. 0° data show large scatter. It is not known what adhesive was used to bond the tabs.

Stress states in tabbed specimens are discussed in some detail in the section on straight sided coupon tension specimens. Typical stress states in an E-glass/epoxy specimen (Figure 4) with tapered and non-tapered ±45° glass/epoxy tab (woven) are shown in Figure 5 [2]. As discussed earlier a stress singularity exists in the ideal elastic problem and all stresses peak at the tab ends [2, 11]. Shear stresses and tensile peel stresses are likely to cause debonding of the tabs (or slightly below the tabs) in that region. In addition fiber failures are likely to occur near tab ends. In unidirectional specimens a failure of the type shown in Figure 18 may sometimes cause very early failures [10, 17].

In many cases (especially in specimens with some cross reinforcements), tab ends are the damage initiation points (Figure 7) and damages grow with increasing load and lowers the strength [2]. It is, however, clear that the stress peaks are lowered with decreasing angle of taper (Figure 5), the worst case being that of tabs with no taper (or 90° taper). Use of long tapered tabs (7° - 10° taper) has been suggested by many investigators to reduce the damages at tab ends [2, 6 - 10]. It may be noted, however, that the stress analysis reported in [2] does not consider the effects of adhesive layer and the pressure imposed by wedge action or hydraulic grips. Effects of adhesive layers (which lowers the axial stress peaks) and wedge action grips have been modeled in [8] and the results show that tensile peel stresses remain high near the tab end except for square end tabs (90°) which terminate inside the grip or flush with the end of the grip. Tensile peel stresses are lowered for the latter cases because of compressive load from the grips. For this reason it has been suggested [17] that soft untapered tabs compressed over the entire length of the grip be used to avoid damages at the tab tips. It may be noted, however, that the shear stresses at tab ends are increased with such 90° tabs. Test data show that strengths from tapered tabs (with angles of the order of 7° to 10°) and those from 90° tabs can be comparable for materials with

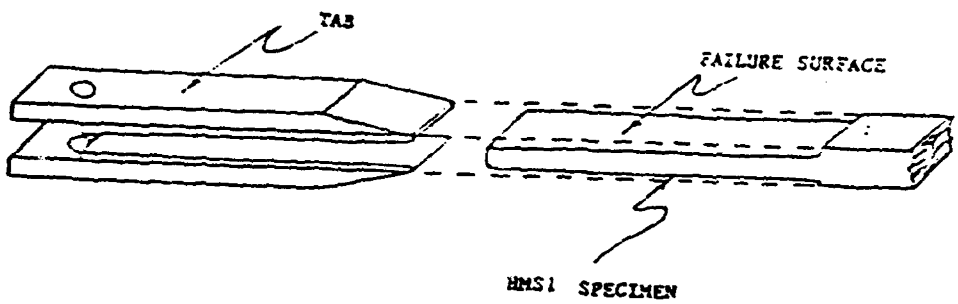


Figure 18. Standard HMS1 Graphite/Epoxy Tab Region Failure [10], Copyright Hercules, Inc., Reprinted with Permission

comparatively high interlaminar shear strength [2]. However, 90° configuration may yield significantly lower strength when the material has low interlaminar shear strength [10]. It has, however, been observed that bonding of tapered tabs is a difficult process and special care and clamping devices are required for such bonding [2]. Otherwise, tabs tend to peel off early and cause premature failure. For this reason use of 90° tabs is economical and may be acceptable [2] if interlaminar shear failure can be avoided.

3.5.3 Effects of Tab Geometry

These effects have been studied analytically [2, 7-9] as well as experimentally [2, 6, 9, 10]. Various geometric parameters studied are shown in Figure 19 (reproduced from [7]). Effects of various parameters on stress peaks are discussed next.

Thickness

Thickness of the tab is not found to have much influence for tapered tabs (10° - 45° [7]).

Taper Angle

As discussed earlier, this parameter has a major effect on the stress peaks. Increasing the angle from 10° to 25° increases the longitudinal stress peaks by only 5%, but causes a two fold increase in shear and peel stresses [7]. 90° unsupported tab ends yield the worst case scenario in both peel and shear stresses. Peel stresses are lower when such tabs are compressed by the grips as discussed earlier. Peak stresses for seven tab configurations (Figure 20) considered in [8] are given in Table 1. The results indicate low taper angles are desirable, even though 90° tabs supported by wedge grips yield less severe peel stresses. There are two reasons for this conclusion, namely; (i) shear stresses remain high and (ii) stresses under gripped 90° tabs are affected by the grip mechanism [8]. Compressive stresses in the tab and the adhesive are strongly influenced by the tab length. On the other hand, stresses under tapered tabs are not influenced much by the length of the tab [7, 8]. However, as mentioned earlier because of problems in bonding of tapered tabs and scatter in data, desirability of tapered tabs can not be collaborated from test data [2]. Low taper angles

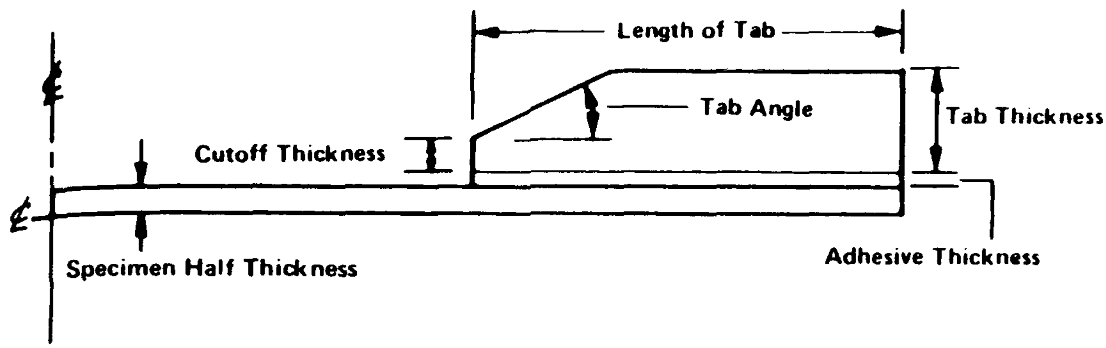


Figure 19. Tab Parameters [7], Copyright ASTM, Reprinted with Permission

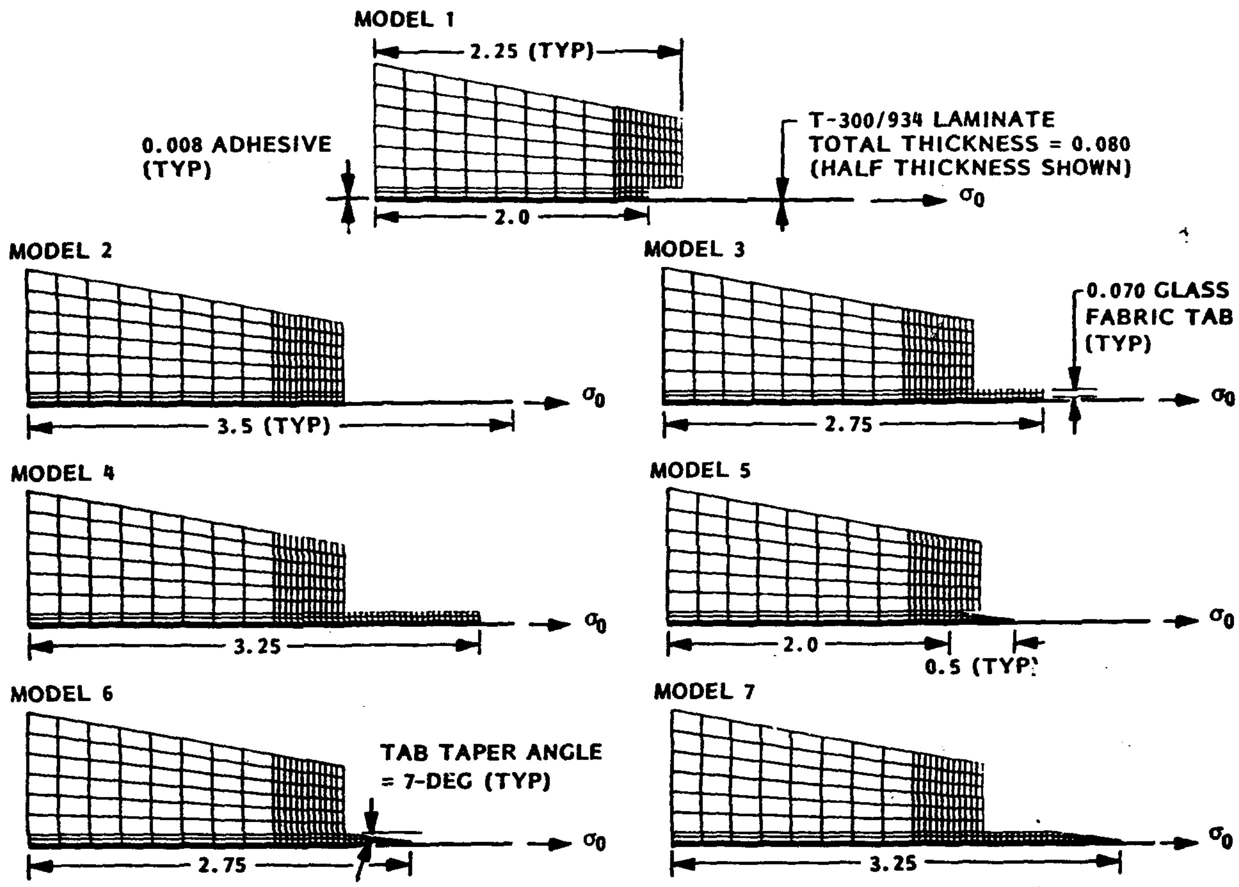


Figure 20. Analytical Models Used in [8], Copyright ASTM, Reprinted with Permission

Table 1. Maximum (Peak) Stresses in Tensile Coupons - Pure Tensile Case Applied
Load σ_0 = 10000 psi [8]
Copyright ASTM. Reprinted with Permission

Model (see Fig. 2)	Maximum Laminate Stresses, psi				Maximum Adhesive Stresses, psi				Maximum Tab Stresses, psi			
	Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7	Column 8	Column 9	Column 10	Column 11	Column 12
	σ_R	σ_Z	σ_T	σ_{RZ}	σ_R	σ_Z	σ_T	σ_{RZ}	σ_R	σ_Z	σ_T	σ_{RZ}
Square End Tabs												
1	10 590	85	231	495	18	-218[b]	-84	720	885	-188[b]	5	689
2	10 550	88	232	479	128	-57[b]	30	711	908	-35[b]	49	672
3	10 370	350	300	341	383	344	306	578	1866	351	157	507
4	10 360	334	295	328	372	330	295	563	1967	338	164	493
Tapered Tabs												
5	10 300	112	235	261	206	87	123	429	1794	90	155	600
6	10300	112	235	260	206	86	123	428	1732	90	150	514
7	10 300	110	235	255	205	86	122	424	1960	90	163	490

[a] *Nomenclature*
σ_R = axial stress,
σ_Z = normal (peel) stress,
σ_T = transverse stress (R-T plane),
σ_{RZ} = interlaminar shear stress, and
1 psi = 6.895 kPa.
[b] Maximum algebraic value

(7° - 10°) always yield higher strengths than higher ones (30° -45°) [2, 7, 10]. It has been suggested [14] that covering the bevel area of tapered tabs with a soft material may help prevent peeling of tabs.

Cut Off Thickness

In case of tapered tabs, stresses are much lower for smaller cut off thicknesses and best results are obtained when the tab ends are feathered to zero thickness [7, 8]. Test data [8] indicate that 80% of specimens tested with 0.254 mm cut off resulted in tab region failures and also showed delamination and longitudinal cracking. On the other hand only 20% of specimens with zero cut off appeared to have tab region failures and the rest exhibited clean tension failures.

3.5.4 Tab Material

In general it appears that compliant tabs are preferable [8], since they yield lower interlaminar stresses. Aluminum tabs do not perform well as compared to fiber glass tabs although Titanium tabs bonded to thin fiber glass layers are acceptable [21]. However, the latter system does not yield much advantage over all fiber glass tabs. Also ±45° glass/epoxy fabric is preferable over (0/90) layups [15, 17]. These results appear to be in agreement with the result [8] that an increase in laminate stiffness lowers the interlaminar stress peaks for similar tabs.

3.5.5 Adhesive

Type of adhesive does not strongly influence the results [21], although it has been found that interlaminar stresses are reduced with a compliant adhesive. Tougher adhesives yield slightly higher strengths [18]. Increase in bond line thickness may have some influence, i.e., slight increase in peel stress but decrease in shear stress [7]. It has, however, been suggested that uniformity of bondline is important to obtain reproducible test data [21].

Use of unbonded tabs with friction devices like medium grip emery cloth particularly with hydraulic grips have been suggested [17]. The tabs should have no taper and terminate inside the grips. There is, however, not much data on whether this approach yields reliable data.

3.5.6 Grips and Clamping Pressures

Use of standard wedge grips with serrated jaws on bonded tapered tabs is the common practice [14]. In such grips the clamping pressure increases with increasing load on the specimen. In this process high clamping pressures are generated at failure loads corresponding to the failure loads of common unidirectional graphite/epoxy specimens. Effects of hydraulic clamping pressures on strengths and ultimate strains of tabbed specimens as reported in [22] are shown in Figures 21 and 22. Both strength and ultimate strain tend to increase with increasing clamping pressure in the beginning, but show a decrease later. Optimum clamping pressure may depend on the laminate and tab stiffnesses. A servo-feedback hydraulic clamping system is needed to ensure constant clamping pressure. Otherwise pressure may drop with increasing load at high values of clamping pressure. Very high clamping pressures tend to cause failure at tab end terminations. Strengths and failure modes at optimum pressures under hydraulic grips are comparable to those from Griff type wedge action grips. This conclusion applies to tabbed specimens.

Testing of untabbed specimens has been attempted [13, 17, 18] since it reduces specimen preparation costs. However, as mentioned earlier, such attempts with currently available standard wedge grips tend to cause damage to surface plies. Hydraulic grips with friction grips provide a means to adjust the clamping pressure so that specimens are not crushed under excessive pressure [17]. Wedges of hydraulic grips with less severe surface texture has also been suggested [18]. There is, however, insufficient data to conclude whether such testing is viable under normal or hot/wet conditions. More tests appear needed for this purpose.

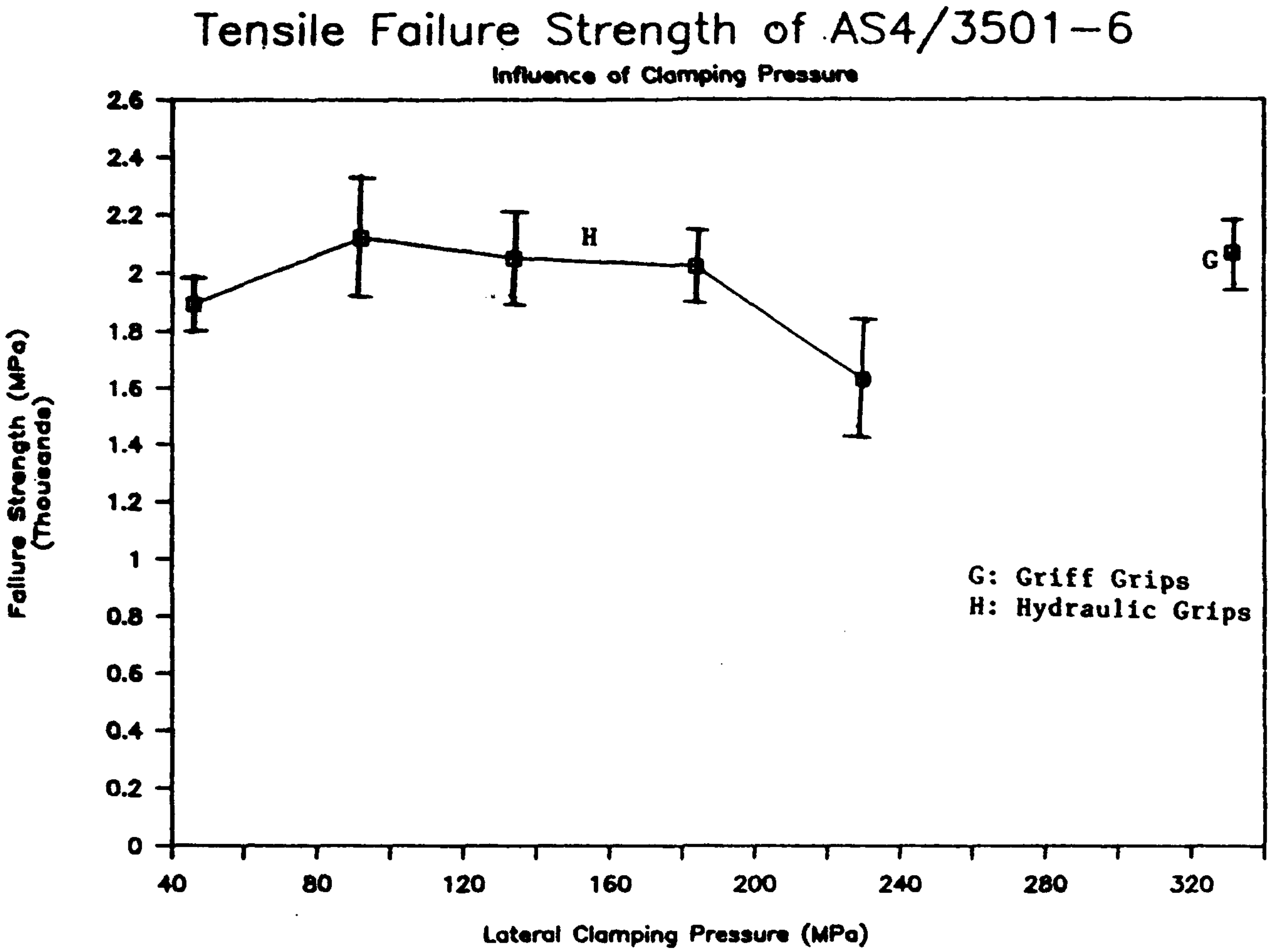


Figure 21. Effect of Clamping Pressure on Failure Strength [22], Copyright Hercules, Inc., Reprinted with Permission

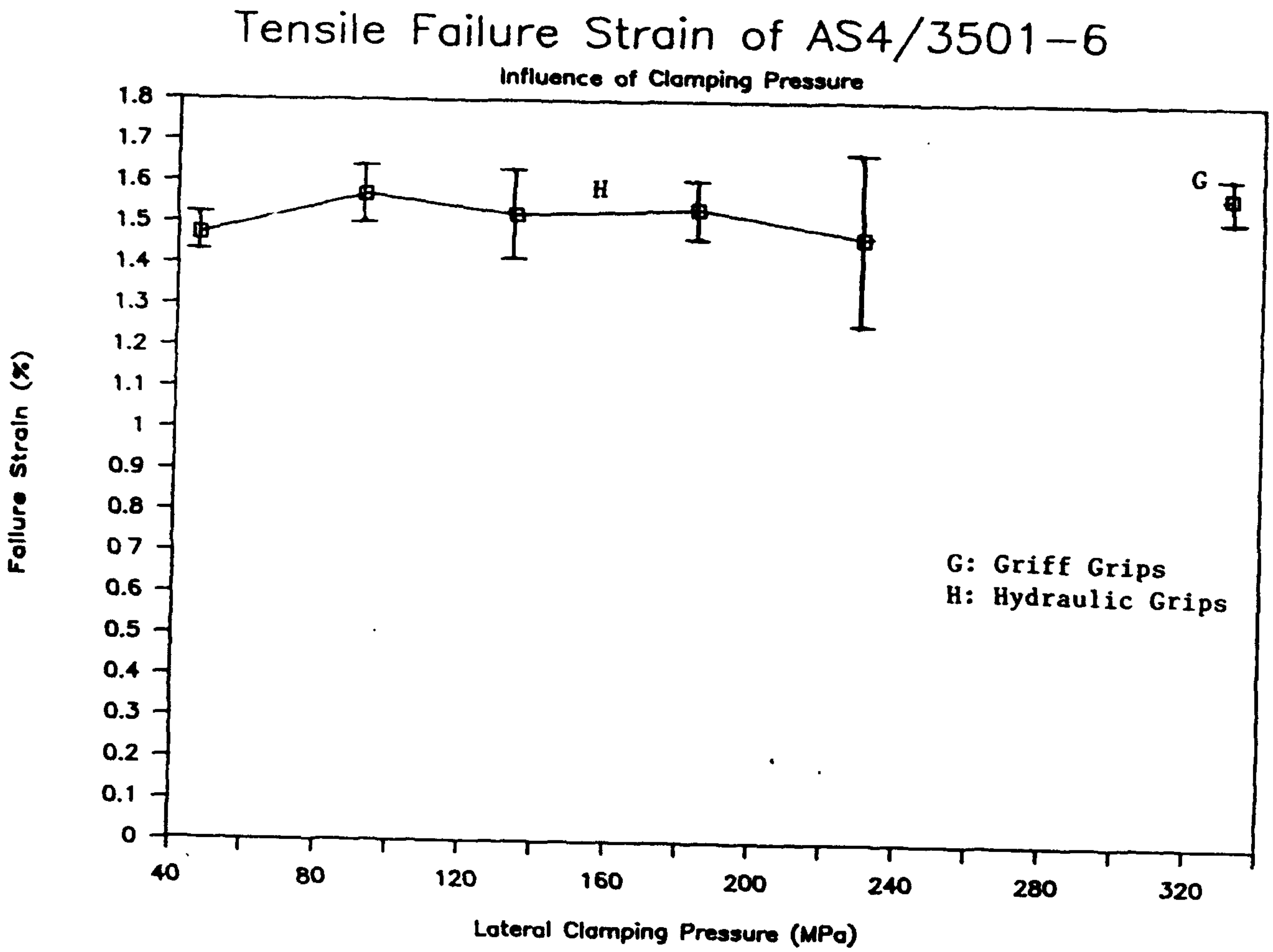


Figure 22. Effect of Clamping Pressure on Failure Strain [22], Copyright Hercules, Inc., Reprinted with Permission.

3.6 TESTING OF LAMINATES WITH CROSS REINFORCEMENTS

3.6.1 General Comments

Because of the strong sensitivity of unidirectional coupon strengths on the misalignment of fibers (discussed in the section on straight sided coupons and illustrated in Figure 8), it has been suggested that properties of unidirectional materials (especially strength) be backed out from tests on specimens with some cross reinforcements [13, 16 - 19]. In [16] it is stated that the best specimen is a 1" wide 9 ply coupon with 0° and 90° alternating plies. The choice of 9 plies instead of 8 or 10 is made to avoid stacking of two plies of same orientation next to each other, so that maximum resistance against splitting can be obtained. A SACMA recommended standard using ASTM Standard D3039 [5] is under development. Establishment of a new standard is being considered by ASTM D30 Committee.

3.6.2 Comparison with 0° Data

Testing 8 ply thick coupons with various arrangements of layers have been performed [13] and the results are reproduced in Figures 23 and 24. The back out factor (1.89 in this case) is the ratio of the calculated cross ply laminate modulus to that of 0° material for both modulus and strength (based on the assumption that the 0° layers should fail at the same strain level). It may be noted 0° data reported in [13] were obtained from specimens manufactured with utmost care in avoiding effects of misalignment and other possible problems at the edges. For this reason strengths from all lay ups (including 0°) are comparable to one another except for the $(0/90)_{2s}$ laminate tested without tabs in which damages to surface layers are suspected to cause lower values of strength (and higher coefficients of variation) as compared to those from other cross ply layups. The coefficient of variation for 0° coupon data is, however, much higher than those for other cross ply specimens. Modulus data for $(90_2/0_2)_s$ show considerable scatter. Reasons for this scatter are not clear, but it may possibly be due to cracking of thick 90° surface layers.

Some comparisons for the following specimen layups for a high strain graphite fiber (Amoco T650-42/1903-4) composite [18] are shown in Figure 25.

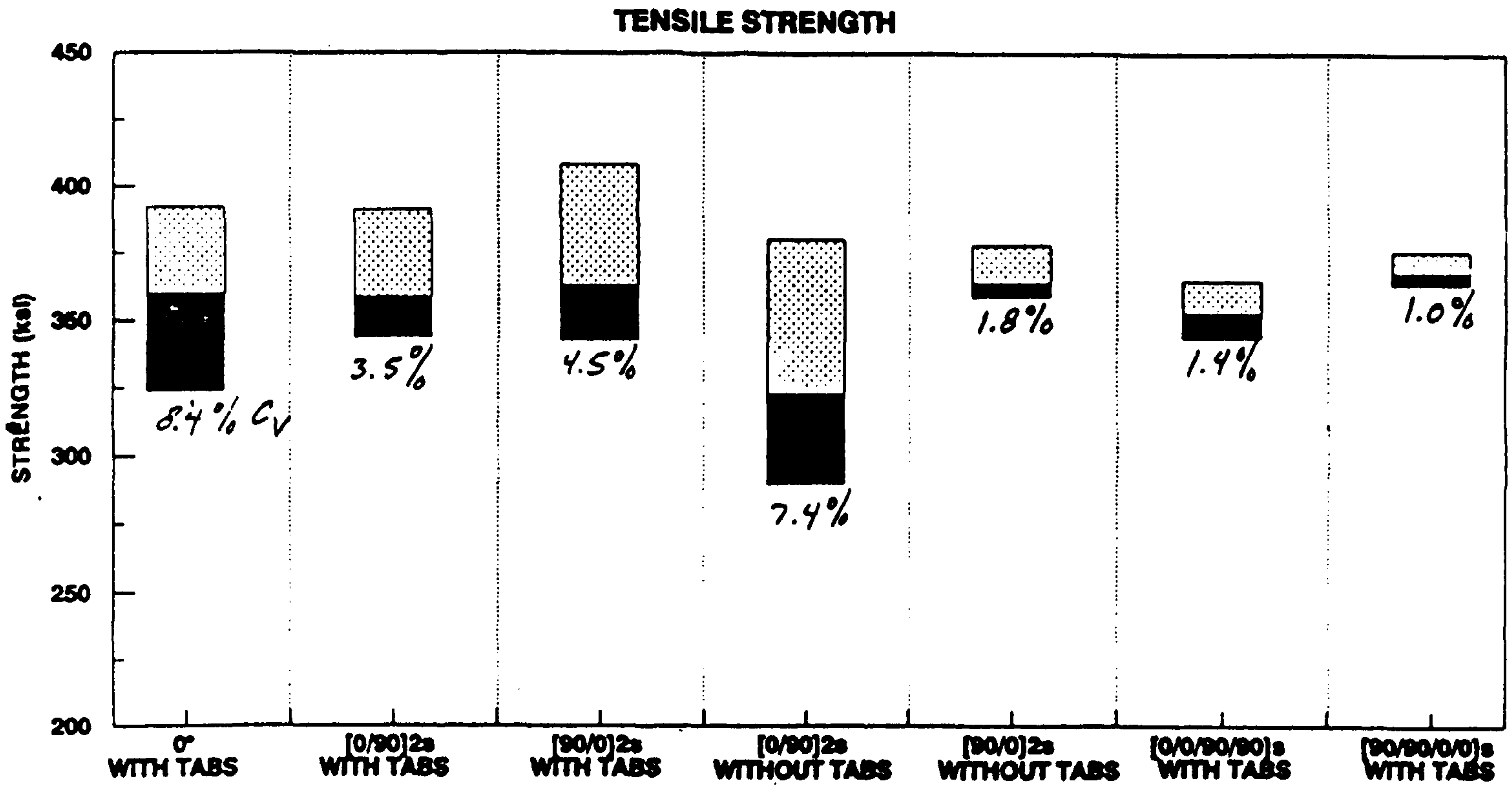


Figure 23. Strength of IM7G/8551-7A [13]

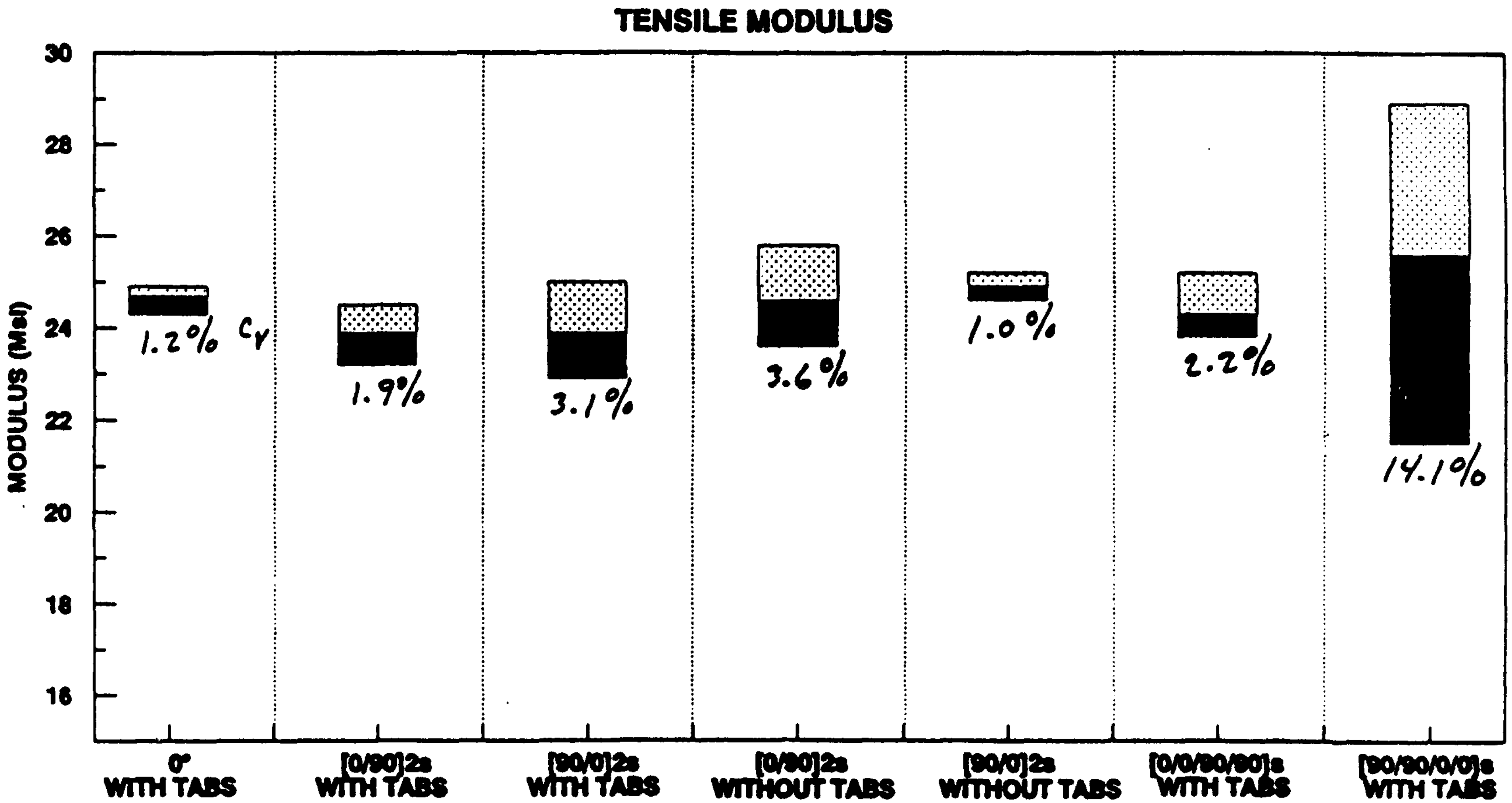


Figure 24. Modulus of IM7G/8551-7A [13]

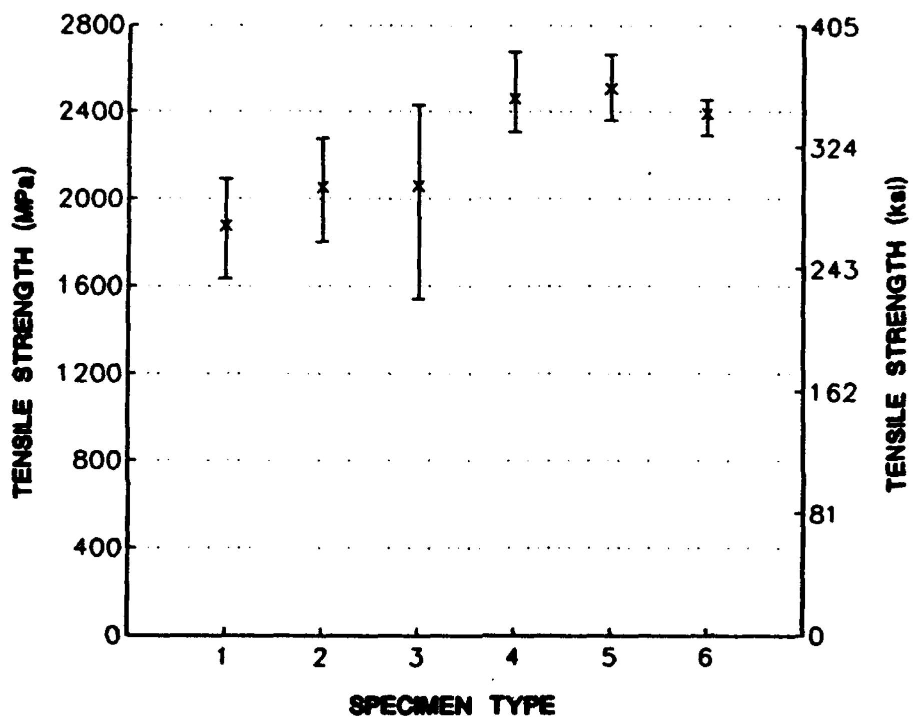


Figure 25. Tensile Strength Data for 6 Specimen Configurations, Material: Amoco T650--42/1903-4 [18] (Courtesy: R.A. Rawlinson, General Electric)

Specimen type, Layup, Tabs (all D3039)	Type No.	Backout Factor
0_8, ½" wide, (0/90) Glass Fabric tab, 15° taper	1	1.0
0_8, ½" wide, ±45 Glass Fabric tab, 15° taper, Tough adhesive	2	1.0
0_8, ½" wide, no tabs	3	1.0
Angle ply - (0/45/0/-45/0/-45/0/45/0) ½" wide, no tabs	4	1.65
Angle ply - (0/45/0/-45/0/-45/0/45/0) 1" wide, no tabs	5	1.65
Cross ply - (0/90/0/90/0/90/0/90/0) 1" wide, no tabs Best specimen as per [17]	6	1.72

The differences in the 0° strength data (specimen types 1-3) are attributed to tabbing variations, the specimens without tabs showing highest scatter. 0° strengths backed out from angle ply and cross ply layups are found to be higher (coefficients of variation lower) than those measured from 0° specimens. It is suggested that the higher strengths are due to the reason that the laminates with cross reinforcements are more tolerant to manufacturing and testing inaccuracies.

Similar comparisons for five Hercules materials at room temperature (Figure 26) and for IM8G/8553 at high temperature (Figure 27) show that in some cases the cross ply specimens yield higher strengths whereas in others they provide data comparable to 0° coupons. However, in all cases the scatter in 0° strengths determined from cross ply specimens are lower. All test data in Figures 26 and 27 are from tabbed specimens.

3.6.3 Data Reduction

The data reduction procedure is currently based on elastic laminate theory. For (0/90) layups the back out factor is given by [23].

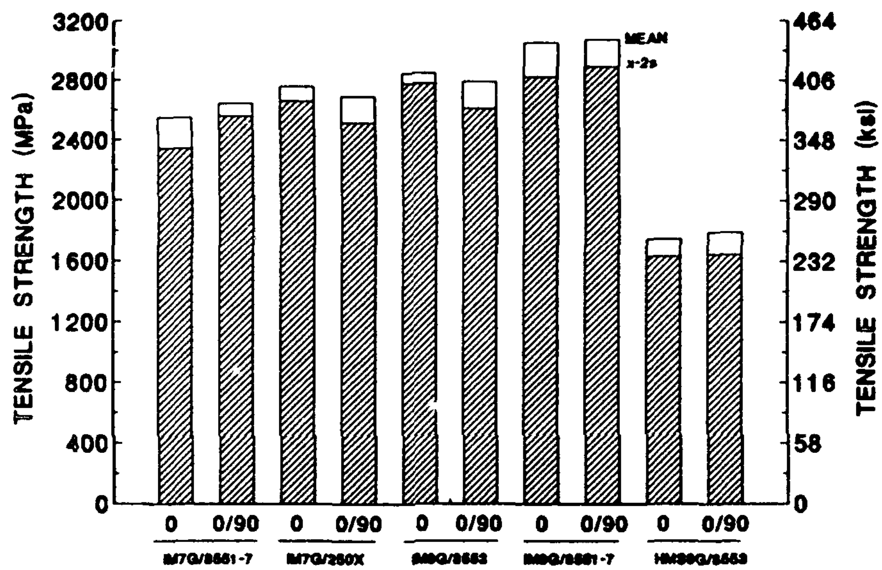


Figure 26. Tensile Strength Data for 5 Herc·les Materials and 2 Specimen Configurations [18] (Courtesy: R.A. Rawlinson, General Electric)

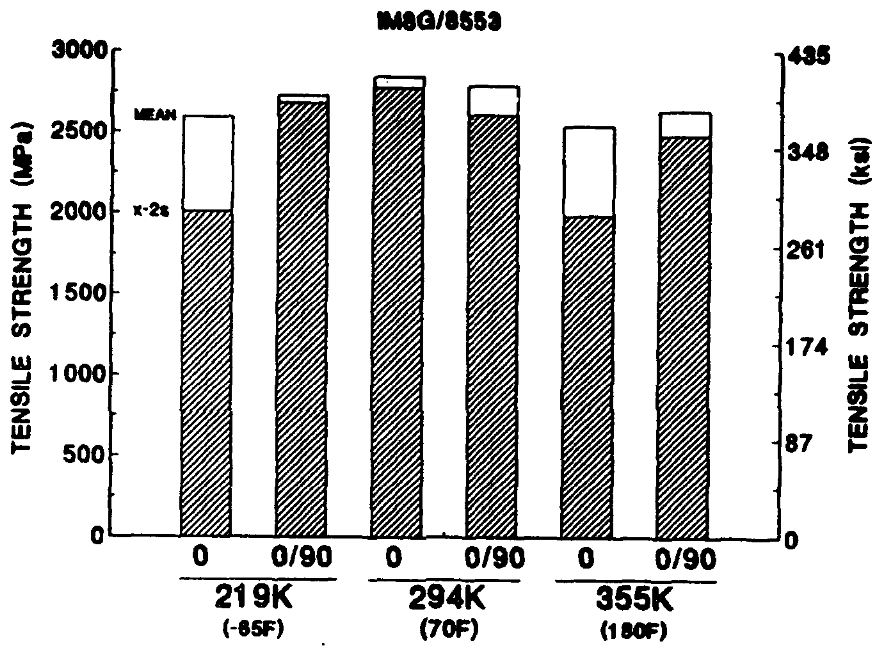


Figure 27. Tensile Strength Data for 2 Specimen Configurations at 3 Temperatures [18] (Courtesy: R.A. Rawlinson, General Electric)

$$F = \frac{E_1[nE_2+(1-n)E_1] - (\nu_{12}E_2)^2}{[nE_1+(1-n)E_2][nE_2+(1-n)E_1] - (\nu_{12}E_2)^2}$$

where E_1, E_2 are the axial and transverse Young's modulus of the unidirectional material, ν_{12} is the axial-transverse Poisson's ratio and n is the fraction of 0° plies.

3.6.4 Discussion

It is known that transverse ply cracks develop in 90° or other off-axis layers in cross reinforced specimens. Residual processing stresses and free edge effects usually causes an increase in ply crack densities [24], especially when the layers are lumped and, therefore, it is advisable to use dispersed layups in cross reinforced specimens. However, in standard graphite/epoxy composites with nearly equal volumes of 0° and cross reinforcing layers, the effect on stiffness reduction is not significant. Thus, the data reduction procedure based on laminate theory discussed in the previous subsection is adequate for such materials, although it may be less accurate for glass/epoxy composites which has a comparatively high transverse modulus as compared to the axial modulus. Sufficiently accurate models are now available in literature to modify the data reduction procedure with due consideration to stiffness loss in 90° layers and load redistribution due to transverse ply cracks. It may be noted, however, that laminate theory will usually yield a conservative estimate of 0° layer strengths. It appears, therefore, that testing of cross reinforced specimens provides a means of reduction in the cost of specimen preparation and avoiding the problems of misalignment and resulting splitting in unidirectional coupons. Comparison of strengths obtained from carefully prepared unidirectional and cross ply specimens for common graphite and glass reinforced thermosets appear necessary before the testing of cross reinforced specimens can be accepted as a standard practice. Not much data are reported for such materials. Testing of cross reinforced specimens without tabs as well as with bonded and friction tabs are also needed to determine whether use of bonded tabs can be avoided. Influence of scissoring effect on performance of specimens with ±45° plies also needs some

investigation, since it has been suggested that (0/90) layups can not be used for testing some new composites [17, 18] and testing of $(0/\pm 45)$ laminates may be the only choice for such composites.

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APPENDIX

ANNOTATED BIBLIOGRAPHY

TENSION TEST METHODS

(Items marked with * are also refernced in body of the report.)

*** ITEM NO. 1**

AUTHORS: Abdallah, M.G., and Muller, C.S.

TITLE: An Experimental Study of the Effect of Clamping Pressure on the Tensile Properties of Unidirectional Graphite/Epoxy Composite Materials

SOURCE: Hercules Inc., Progress Report

pp:

DATE: March, 1987

TEST SPECIMENS: Tabbed Straight Sided

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - Y

REMARKS: Tests were conducted with hydraulic grips (for prescribed clamping pressures) as well as Griff type wedge action grip. As hydraulic grip clamping pressure was increased, strength (as well as scatter) increased and then decreased. The Griff type gripping system produced less scatter in strength and strengths comparable to those from specimens with hydraulic grips at optimal clamping pressures. It was noted that in the Griff type gripping system the clamping pressure increased with increasing load on the specimen and at failure loads the pressure was much higher than the optimal values of pressures in the hydraulic gripping system. Similar results in stiffness values are also reported for the two types of gripping systems. It was also observed that it was difficult to control the clamping pressure in hydraulic grips. At low pressures, the pressure appears to decrease and then increase as the load was increased. At high pressures the pressure level appeared to decrease with increasing load. It is not clear whether this phenomenon caused the strength and modulus values to reduce at high clamping pressures.

Photoelastic studies revealed a uniform stress distribution in the test section with no effect of clamping pressure. At low hydraulic clamping pressures and clamping using Griff type grips specimens failed in the test section with some fiber splitting. At high clamping pressure longitudinal fiber splitting was observed with final failure at tab end terminations. These splits usually started either at tab ends or from the sides where fibers appeared to have been cut.

• ITEM NO. 2

AUTHORS: Abdallah, M.G., and Westberg, R.L.

TITLE: Effect of Tab Design of the ASTM D3039 Tension Specimen on Delivered Strength for HMS1/3501-6 Graphite/Epoxy Material

SOURCE: Proc. 1987 SEM Spring Conference on Experimental Mechanics

pp: 362-366

DATE: 1987

TEST SPECIMENS: Tabbed Straight Sided

CONTENTS:

Experimental Results? [Y/N] - Y Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - Y

REMARKS: Standard (14° taper), no taper, and two other tab configurations (both with 7° taper, one slightly longer in the flat portion) were investigated. 0/90 fiber glass tabs (.065" thick) were used. Tests conducted with 7° taper tabs (both of the configurations) showed higher strength and less scatter than those with standard 14° taper and no taper. The latter type specimens often showed failure underneath the tab with tabs and parts of the surface plies shearing off, whereas small taper angles produced tensile failure mode in the specimen gage section.

• ITEM NO. 3

AUTHORS: Bert, C.W.

TITLE: Static Testing Techniques for Filament-Wound Composite Materials

SOURCE: Composites, 5

pp: 20-26

DATE: January, 1974

TEST SPECIMENS: Dogbone, Straight Sided, Notched Straight Sided

CONTENTS:

Experimental Results? [Y/N] - N   Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - N

REMARKS: Surveys various specimens. Tabbed straight sided, dogbone and a straight sided coupon with two small notches at the center are described. The last two specimens are not believed to be good choices because of early failure due to stress concentrations. Tabbed straight sided coupon with serrated jaw type end connection (as opposed to pin loaded or multihole type) is judged to be the best for unidirectional materials. Even 1° misalignment (between fiber and loading direction) may cause severe reduction in strength as well as modulus and special care is suggested to avoid such imperfections.

*** ITEM NO. 4**

AUTHORS: Camponeschi, E.T., Jr., and Hoyns, D.

TITLE: Determination of Effective [0] Properties from [0/90] Laminate Testing

SOURCE: ASTM D30-04 Spring 1991 Meeting

pp:

DATE: 1991

TEST SPECIMENS: Cross Ply Testing

CONTENTS:

Experimental Results? [Y/N] - N   Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - N

REMARKS: Gives back out factors for determining [0] properties from various [0/90] laminates.

*** ITEM NO. 5**

AUTHORS: Cernosek, J. and Sims, D.

TITLE: The Effect of Tab Geometry on the Fatigue Life of Fibrous Composites

SOURCE: Experimental Techniques

pp: 5-11

DATE: December, 1982

TEST SPECIMENS: Tabbed Straight Sided

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - N

REMARKS: Finite element analysis results show that ASTM D3039 specimen with a 7° tapered tab with a soft material over the bevel area can suppress peeling of the tabs. Proposed geometry does not have any influence on static strength, but increases fatigue life under tension-tension fatigue.

*** ITEM NO. 6**

AUTHORS: Cunningham, M.E., Schoultz, S.V., and Toth, J.M., Jr.

TITLE: Effect of End-Tab Design on Tension Specimen Stress Concentrations

SOURCE: ASTM STP 864

pp: 253-262

DATE: 1985

TEST SPECIMENS: Tabbed Straight Sided

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - N

REMARKS: Effects of thickness, angle, cut-off thickness, length and stiffness of tabs on stresses near tab ends are studied. Adhesive stiffness and thickness effects are also examined.

Thickness of tab does not influence the stress concentration for 10° as well as 45° taper angles. Increasing the taper angle increases the stresses, especially the interlaminar ones (70% change in shear stress when angle is changed from 10° to 25°). A 10° angle is chosen for other studies. Changing cut off thickness from 0 to .01" increases peel and interlaminar shear stresses by 750 and 200%. Peek stresses do not differ much under 0° or (0/90) fiber glass tabs, but are too high for 0° graphite/epoxy tabs. Larger adhesive thickness reduces peel stress, but stiffer adhesive causes some increase in this stress. Tests data indicate that 10° taper and no cut off yields less scatter and higher strength (as compared to .01" cut off and 10° taper) and acceptable failure modes away from tab ends.

*** ITEM NO. 7**

AUTHORS: Dastin, S., Lubin, G., Munyak, J., and Slobodzinski, A.

TITLE: Mechanical Properties and Test Techniques for Reinforced Plastic Laminates

SOURCE: ASTM STP 460

pp: 13-26

DATE: 1969

TEST SPECIMENS: Dogbone, Straight Sided, Modified Bowtie

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - Y

REMARKS: The bowtie (long neck) specimen is found to be superior to dogbone (ASTM D638) on tabbed straight sided coupons. Failures in bowtie specimens are found to occur in the gage section. All D638 specimens (with varying shoulder radii 3", 8" and 18") show failures at the shoulder and lower strengths. Motion pictures show that a micro explosion occurs at break with shattering of glass fibers and release of glass and resin at one location. It is inplane for bowtie and D638, but out of plane in tabbed specimens. These explosions occur after generation of a micro delamination (a dark spot away from the edges) and its progression inward (not towards the edges). Bowtie specimen can work all right up to 450°F.

ITEM NO. 8

AUTHORS: Elkin, R.A., Fast, G., and Hanley, D.P.

TITLE: Characterization of Graphite Fiber/Resin Matrix Composites

SOURCE: ASTM STP 460

pp: 321-335

DATE: 1969

TEST SPECIMENS: Tabbed Straight Sided

CONTENTS:

Experimental Results? [Y/N] - Y Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - Y

REMARKS: Straight sided coupons with bonded premolded fiber glass tabs gripped by self tightening serrated face jaws are used. A room temperature curing adhesive is used to avoid problem due to mismatch of thermal expansion. A centering jig is used for mounting and alignment. Failure modes vary (from extensive splintering with failures at many locations to failure straight across a section) depending on material. 90° specimens are tested without tabs, but with pneumatically activated rubber faced jaws, since loads required are small.

* ITEM NO. 9

AUTHORS: Hadcock, R.N., and Whiteside, J.D.

TITLE: Special Problems Associated With Boron-Epoxy Mechanical Test Specimens

SOURCE: ASTM STP 460

pp: 27-36

DATE: 1969

TEST SPECIMENS: 0° Straight Sided Coupon With Tapered Tabs

CONTENTS:

Experimental Results? [Y/N] - Y　　Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - Y

REMARKS: Fiberglass tabs with 20°-30° taper angles cause failure in tab regions. Thinner specimens (6 ply) with long (3½") fine taper tabs perform better. Polished edges yield higher strengths and less scatter. Preloading to 75% of ultimate raises proportional limit and reduces variations in measured modulus. Evaluation of results based on load/unit width/layer basis reduces scatter due to thickness variations. Gripping and alignment in environmental chamber can be made easier by extending the tabs to accommodate pins seated in V grooves on the grips. Testing at high temperature (350°F) needs improvement since 50% of failures occur in tabbed regions.

*** ITEM NO. 10**

AUTHORS: Hansen, G

TITLE: Cross Ply Test Results

SOURCE: MIL-HDBK-17 Meeting

pp:

DATE: April, 1989

TEST SPECIMENS: Tabbed and Untabbed Straight Sided Laminate Coupons

CONTENTS:

Experimental Results? [Y/N] - Y　　Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - N

REMARKS: Presents results for the following laminates - some with and some without tabs.

(i) 0°, (ii) $(0/90)_{2s}$, (iii) $(90/0)_{2s}$, (iv) $(0/90)_{2s}$ without tabs, (v) $(90/0)_{2s}$ without tabs, (vi) $(0/0/90/90)_s$, $(90/90/0/0)_s$

Cross ply results appear to show strengths which are comparable to 0° data (but with less scatter) except in the case of $(0/90)_{2s}$ without tabs. Modulus obtained from $(90/90/0/0)_s$ with tabs show high scatter for

unknown reasons (it is quite possible some of the specimens may contain initial transverse cracks in outer 90° layers thus creating problems in strain measurement). It is suggested that 0° specimen tests have been performed with considerable care. Similar care is not needed in (0/90) tests. Such tests may be preferred if process steps are less critical.

*** ITEM NO. 11**

AUTHORS: Hart-Smith, L.J.

TITLE: Some Observations About Test Specimens and Structural Analysis for Fibrous Composites

SOURCE: ASTM STP 1059

pp: 86-120

DATE: April, 1988

TEST SPECIMENS: Tabbed Straight Sided, Dogbone, Cross Ply Testing

CONTENTS:

Experimental Results? [Y/N] - N Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - N

REMARKS: Tab misalignments, unequal tapers, variation or irregularity in the thicknesses of tabs or adhesive layers and excessive tab tip thicknesses are pointed out to be problems in ASTM D3039 specimens, which cause early failures. It is suggested that better results are obtained without the use of tabs and employing abrasive-coated wire mesh or emery paper as interleaf between the specimen and the jaws of test fixture.

Results of tabbing variation and misalignment (item 10) are discussed. It is suggested that the misalignment effectively reduces the width of the specimen because of interfiber splitting in the whole specimen due to misalignment. The problem becomes severe because of large length to width ratio. Improvement in strength after polishing the edges as reported in some studies is also discussed.

* **ITEM NO. 12**

AUTHORS: Hart-Smith, L.J.

TITLE: Generation of Higher Composite Material Allowables Using Improved Test Coupons

SOURCE: 36th International SAMPE Symposium

pp: 1029-1044

DATE: 1991

TEST SPECIMENS: Straight Sided, Cross Ply Testing

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - N

REMARKS: Problems in tabbed specimens are discussed. A 1" wide straight sided 9-ply thick crossply (alternating 0° and 90° layers avoiding lumping of two layers near the midplane) specimen with friction tabs is proposed. Results from (0/90) and (0/±45) coupon tests made by various organizations (see item 13) are presented. It is noted that damages in outer plies result in a large scatter in 0° tabless test. Test data from cross ply tests show higher strengths and less scatter. It is suggested that extreme care in testing (good quality panels and specimens without misalignments) can yield comparable strengths. Strengths of slightly misaligned panels are lower, not because of such misalignment, but due to the unforgiving nature of D3039 specimens.

Cross ply testing may be a problem in some new composites with extremely high temperature cure resins, for which it may be very difficult to fabricate (0/90) laminates because of splitting due to residual thermal stresses. (0/±45) testing may be a better choice under such circumstances.

Peel stress induced damage is a problem in bonded tapered tabs. It is suggested that this kind of damage can be avoided by using untapered soft ±45 tabs compressed over entire length by the grips. A better choice is the use of unbonded tabs with friction grips which, however, may not be suitable for hot/wet testing.

*** ITEM NO. 13**

AUTHORS: Kessler, J.A., and Adams, D.F.

TITLE: Composite Specimen Design Analysis - Vol. II. Experimental Efforts

SOURCE: MTL TR 91-5

pp:

DATE: January, 1991

TEST SPECIMENS: Tabbed Straight Sided, Bowtie and Streamline

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - Y

REMARKS: Moduli and strength from the three specimens are compared. Modulus and strength from tabbed 0° specimens are found to be higher than those from bowtie and streamline specimens. Cross ply data are comparable with the tabbed specimens showing slightly lower strength. Many splits were noticed in all bowtie and streamline 0° specimens (at 60% of ultimate load) before final failure in the form of a transverse brittle fracture perpendicular to the specimen axis about an inch away form gripped area. The tabbed 0° specimens literally disintegrated upon failure. All cross ply specimens tended to fracture into two distinct pieces by a single transverse crack. Tabbed specimens generally failed in the gage section with considerable delamination in the vicinity of the primary fracture, but with little splitting. Bowtie and streamline specimens often occurred outside of test section. Longitudinal cracks (splits) were also present.

*** ITEM NO. 14**

AUTHORS: Kistner, M.D., Whitney, M.J., and Browning, C.E.

TITLE: First Ply Failure of Graphite/Epoxy Laminates

SOURCE: ASTM STP 864

pp: 44-61

DATE: 1985

TEST SPECIMENS: Tabbed Straight Sided Laminates

CONTENTS:

Experimental Results? [Y/N] - Y Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - N

REMARKS: Transverse ply cracks in laminates are measured (viewed at polished edges) as a function of applied load. Plateau in longitudinal or transverse stress strain curves are associated with a significant increase in transverse ply crack density. Inplane stresses are found to differ from classical theory near the free edge, which also depend on stacking sequence. It is thought that onset of ply cracks can be influenced by the free edge and the stacking sequence.

*** ITEM NO. 15**

AUTHORS: Kural, M.H., and Flaggs, D.L.

TITLE: A Finite Element Analysis of Composite Tension Specimens

SOURCE: Composite Technology Review

pp: 11-17

DATE: Spring, 1983

TEST SPECIMENS:

CONTENTS:

Experimental Results? [Y/N] - N Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - N

REMARKS: Seven tab configurations were studied. Peak stresses at tab ends are found to be sensitive to tab length, thickness and test laminate stiffness. Stresses are found to be lower for tapered tab geometry with taper angles of the order of 7° feathered at the test section end. These stresses are also not sensitive to the length of the tab indicating that they are not affected by the grip mechanism. Square (90°) tabs on the other hand are adversely influenced by the grip mechanism when the tab end is in the gripped area. Out of plane bending can cause significant increase in peak stresses, the effect is, however, less for tapered tabs. Such stresses also increase with

the tab length. In general , peak stresses reduce when the tab is softer. It is pointed out that theoretical advantage of tapered tabs can be overcome by defective bonds which may result due to tapered tab geometry.

*** ITEM NO. 16**

AUTHORS: Lenoe, E.M.

TITLE: Testing and Design of Advanced Composite Materials

SOURCE: ASCE Meeting, Pittsburgh

pp:

DATE: 1968

TEST SPECIMENS: Various

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - N

REMARKS: Stress analysis results show stress concentration in outer fibers in tab regions indicating possibility of failure and showing problems in load transfer.

*** ITEM NO. 17**

AUTHORS: Lenoe, E.M., Knight, M., and Schoene, C.

TITLE: Preliminary Evaluation of Test Standards for Boron Epoxy Laminates

SOURCE: ASTM STP 460

pp: 122-139

DATE: 1969

TEST SPECIMENS: Straight Sided Laminate Coupons

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - N

REMARKS: Normal care in cutting and standard specifications for adhesive are adequate for specimen preparation and fiber glass tab application. Aluminum tabs yield grip failures. Fiber glass tabs (with or without titanium outer layers) are adequate up to post cure temperature of adhesive. Most of the common adhesives perform well, however, thin uniform bondline is needed for better specimen alignment (and less scatter) specially for 0° specimens. Strain rate sensitivity of resin is important in angle ply laminates. Effects of geometry variations (width, thickness, length) on 0° specimens are not clear because of scatter. Longer and wider coupons are needed for 90° test to reduce problems due to bowing. Strengths of cross and angle ply laminates are affected by width variations, crossply and (±22°) layups yielding highest strengths for smallest width (=0.5").

*** ITEM NO. 18**

AUTHORS: Manders, P.W., Kowalski, I.M.

TITLE: The Effect of Small Angular Fiber Misalignments and Tabbing Techniques on the Tensile Strength of Carbon Fiber Composites

SOURCE: 32nd SAMPE Symposium

pp: 985-996

DATE: 1987

TEST SPECIMENS: Tabbed Straight Sided

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - Y

REMARKS: Small angular misalignments of fibers by as little as 1° reduce the strength. Specimens cut 1° off-axis and tested on axis can cause 30% reduction. Fibers in alternating plies off by ±1° can also reduce the strength, but specimens cut on axis but tested 1° off-axis do not cause much reduction.

Fibers with lower levels of surface functionality are more sensitive because lower adhesion to matrix promotes splintering mode of failure.

Compliant ±45° (as opposed to 0/90) glass/epoxy tabs with 5° taper are found to be effective in preventing premature debonding and splintering in high strength composites.

*** ITEM NO. 19**

AUTHORS: Oplinger, D.W., Gandhi, K.R, and Parker, B.S.

TITLE: Studies of Tension Test Specimens for Composite Material Testing

SOURCE: AMMRC TR 82-27

pp:

DATE: April, 1982

TEST SPECIMENS: Straight Sided, Dogbone, Bowtie, Streamline

CONTENTS:

Experimental Results? [Y/N] - Y Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - Y

REMARKS: Stress analyses and data correlation with due consideration to stress concentration factors are reported for the first three specimens. Bondline stresses in tabbed specimens (subjected to displacements on tab surfaces) show peaks near the tab end, severity decreasing with lower taper angles. Results indicate a stress singularity at the tab end and the possibility of debonding. Dogbone (D638) specimens show stress concentrations at the shoulder. Bowtie specimens also show similar effects near the points where the tapered sides meet the straight edges of the gage section, severity decreasing with lower taper angle (5% appear acceptable). Failure mechanisms due to fiber breaks near peaks in axial stresses and debonding or cracking due to shear are discussed. For tabbed specimen 90° (no taper) and 10° taper with proper care to clamp bevel during tab application appear adequate. Flat specimens need well designed transition regions. Ideas for developing streamline specimens are described.

*** ITEM NO. 20**

AUTHORS: Oplinger, D.W., Parker, B.S., Gandhi, K.R., Lamothe, R., and Foley, G.

TITLE: On the Streamline Specimen for Tension Testing of Composite Materials

SOURCE: ASTM STP 864

pp: 532-555

DATE: 1985

TEST SPECIMENS: Streamline, Dogbone, Bowtie, Tabbed Straight Sided

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - Y

REMARKS: Stress concentration effects [see Item 8] and resulting reductions in strength are discussed. Failure location distribution in tabbed Kevlar/ epoxy specimens show that all failures may be called tab failures as per ASTM D3039. This problem is more severe for hot/wet conditions. Ideal and practical designs for streamline specimen are discussed. Some machining problems are addressed, but further improvements in this area are needed. It is suggested that results be correlated with nominal (not actual) thickness if there is too much thickness variation in a panel. Properly machined streamline specimens are found to perform well. They are preferable over tabbed specimens for hot/wet and fatigue testing. Heat generation and associated problems are less in fatigue testing with streamline specimens.

*** ITEM NO. 21**

AUTHORS: Rawlinson, R.A.

TITLE: The Use of Cross Ply and Angle Ply Composite Test Specimens to Generate Improved Material Property Data

SOURCE: 36th International SAMPE Symposium

pp: 1050-1067

DATE: 1991

TEST SPECIMENS: Straight Sided Coupon, Cross Ply and Angle Ply Specimens

CONTENTS:

Experimental Results? [Y/N] - Y Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - Y

REMARKS: Reports results of a series of programs.

1. 0° tension (D3039) and compression (Modified D695) tests in five laboratories. Good quality specimens were supplied. Tension data are similar, compression data differ due to problems in fixtures used.

2. (a) 0.5" wide $[0]_8$ without and with two types of glass fabric tabs (0/90 and ±45 with 15° taper, later with tough adhesive);
(b) [0/45/0/-45/0/-45/0/45/0] - 0.5" and 1" wide without tabs
(c) [0/90/0/90/0/90/0/90/0] - 1" wide without tabs.

   Tab region failures yielded lower strengths for $[0]_8$, ±45 tabs with resilient adhesive yielding slightly higher results. Use of 7° taper is suggested. Scatter was very high for untabbed $[0]_8$ specimens, due to damage in outer plies. Specimens of the types (b) and (c) yield higher strengths and less scatter.

3. 0° with tabs and various (0/90) specimens, some with and some without tabs with constant hydraulic pressure (required to break $[0]_8$) - Results are comparable except for $(0/90)_{2s}$ without tabs. Damage of untabbed specimens under grips may be a problem.

4. Low and elevated temperature testing 0 and (0/90) specimens - Results show equivalence of 0 and (0/90) data.

   It is suggested that $[0]_8$ D3039 performs well if panels and specimens are prepared with care. Tabbed 0° and (0/90) yield similar data but sometimes cross ply data show less scatter. Cross ply specimens work well for different thermosets as well as thermoplastics at room and elevated temperatures. Testing cross and angle ply (0/45/-45) specimens appears to be a feasible alternative of testing 0° specimens and less expensive.

*** ITEM NO. 22**

AUTHORS: Rawlinson, R.A.

TITLE: Tension Test Results

SOURCE: MIL-HDBK-17 Meeting

pp:

DATE: April, 1989

TEST SPECIMENS: Tabbed and Untabbed Straight Sided Laminate Coupons

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - N

REMARKS: Present test data of test program No. 2 discussed in item 13.

*** ITEM NO. 23**

AUTHORS: Rothman, E.A., and Molter, G.E.

TITLE: Characterization of the Mechanical Properties of a Unidirectional Carbon Fiber Reinforced Epoxy Matrix Composite

SOURCE: ASTM STP460

pp: 72-82

DATE: 1969

TEST SPECIMENS: Tabbed Dogbone

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - Y

REMARKS: Tabbed area is calculated based on average shear stress in the area at anticipated failure load. Vise grips are used. Regripping is tried when bending strains exceed 5% of average tensile strain. Data show lot of scatter especially in strength. Fiber fractures were found to occur randomly, but axial separation (interlaminar shear mode) and extension of fracture surfaces to shoulder areas are noticeable in many specimens.

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